Integrated Global Carbon Observing Strategy

A Strategy to Build a Coordinated Operational Observing System of the Carbon Cycle

Ph. Ciais, B. Moore, W. Steffen, M. Hood, S. Quegan, J. Cihlar, M. Raupach, I. Rasool, S. Doney, C. Heinze, C. Sabine, K. Hibbard, D. Schulze, M. Heimann, A. Chédin, P. Monfray, A. Watson, C. LeQuéré, P. Tans, H. Dolman, R. Valentini, O. Arino, J. Townshend, G. Seufert, C. Field, T. Igrashi, C. Goodale, A. Nobre, G. Inoue, D. Crisp, D. Baldocchi, J. Tschirley, S. Denning, W. Cramer, R. Francey, D. Wickland

1. Executive Summary

The overall goal of the Integrated Global Carbon Observing theme is to develop a flexible yet robust strategy for deploying global systematic observations of the carbon cycle over the next decade. This report sets forth an Operational Global Carbon Observing System. This System has two main objectives:

- To provide the long-term observations required to improve understanding of the present state and future behaviour of the global carbon cycle, particularly the factors that control the global atmospheric CO_2 level.
- To monitor and assess the effectiveness of carbon sequestration and/or emission reduction activities on global atmospheric CO_2 levels, including attribution of sources and sinks by region and sector.

The System will meet those objectives by routinely quantifying and assessing the global distribution of CO_2 fluxes exchanged between the Earth's surface and the atmosphere, and by measuring at regular intervals the changes of key carbon stocks, along with observations that help elucidate underlying biogeochemical processes. The Global Carbon Observing System integrates across all multi-faceted aspects of the three major domains of the carbon cycle: ocean, land, and atmosphere; Indeed, the most successful advances in understanding springs from the combination of data and models for the different domains, wherein results from one domain place valuable constraints on the workings of the other two.

Implementing the observing System requires:

- Establishing data requirements, designing network configurations, and developing advanced algorithms for operational carbon observations, which will be the core of a future, sustained operational system by 2015,
- Developing cost-effective, low maintenance, *in situ* sensors for atmospheric CO_2, ocean dissolved pCO_2, and terrestrial ecosystem fluxes,
- Developing and implementing technologies for remote sensing of CO_2 from space,
- Improving estimates of biomass based on national inventories and/or remote sensing observations,
- Developing, operational carbon cycle models, validated through rigorous tests and driven by systematic observations that can deliver routine diagnostics of the state of the carbon cycle, and
- Enhancing data harmonization and intercomparability, archiving, and distribution to support model development and implementation

This Report presents a vision of the Global Carbon Observing System, which ultimately will be implemented both by research and operational agencies, and it provides a roadmap to realize the System. The Report identifies a core set of existing research-based observations upon which to build the System. It draws heavily from the Terrestrial Carbon Observing strategy as well as documents that describe the Global Climate Observing System, the Global Terrestrial Observing System, and Global Ocean Observing System. In addition, it describes the critical priorities and steps required to transfer the core set of research observations into an operational system.

The Strategy for Operational Global Carbon Observing System is first a carbon crosscut of GCOS, GTOS, and GOOS and second an identification of new components not previously identified. The System is, in effect, a system of systems.

The Operational Global Carbon Observing System should be built around complementary core groups of observations to address three themes: Fluxes, Pools, and Processes.

Fluxes. The first set of observations enables quantification of the distribution and variability of CO_2 fluxes between the Earth's surface and the atmosphere. It contains:

- Satellite observation of column integrated atmospheric CO_2 distribution to an accuracy of at least 1 ppm with synoptic global coverage – all latitudes, all seasons;
  - *These observations do not exist yet and must be given a very high priority.*
- An optimized operational network of atmospheric *in situ* stations and flask sampling sites with an accuracy of at least 0.1 ppm;
  - *These observations, at present, are achieved in research mode, comprise 100 stations worldwide. They must be increased in horizontal and vertical coverage to include continental interiors and poorly sampled regions. This requires development of cost-effective sensors and the systematic use of platforms of opportunity.*
- An optimized, operational network of eddy covariance towers measuring on a continuous basis the fluxes of CO_2, energy and water vapour over land ecosystems;
  - *These observations are currently made from a research network comprising 100 towers. The network must be secured for the long term, and expanded over ecosystem types, successional stages, and land-use intensities.*
- A global ocean pCO_2 measurement system using a coordinated combination of research vessels, ships of opportunity, and autonomous drifters;
  - *These observations represent at present about 100 cruises. The central challenge to developing a global-scale operational ocean carbon observation network is the lack of accurate, robust, cost-effective, autonomous sensors for ocean pCO_2.*
- A combination of satellite observations, backed up by a long-term continuity of measurements, delivering global observations of parameters required to estimate surface-atmosphere CO_2 fluxes where direct *in situ* measurements are scarce.
  - *These crucial satellite observations are: land cover status, disturbance extent and intensity, parameters related to vegetation activity, ocean colour, and ancillary atmospheric and oceanic variables controlling the fluxes.*

The approach for using these observations to quantify the distribution and variability of CO_2 fluxes between the Earth's surface and the atmosphere requires reconciliation of both down-scaling and up-scaling estimates. Atmospheric transport models are required to down-scale the atmospheric CO_2 measurements into fluxes. Carbon cycle flux models are required to scale-up point-wise *in situ* observations using remotely sensed variables.

Once the Operational Carbon Observing System is in place, model-data fusion techniques will routinely assimilate the above listed data streams of carbon measurements to produce consistent and accurate estimates of global CO_2 flux fields with typical resolution of 10 km over land and 50 km over oceans with weekly frequency.

Pools. The second set of observations focuses upon changes in the three key carbon pools:

- Forest aboveground biomass, which will be measured at 5-year intervals by *in situ* inventory methodologies and more frequently by remote sensing techniques.
- Soil carbon content will be measured at 10-year intervals primarily by *in situ* inventory methodologies..
- ➢ *These observations are already collected on a systematic basis for assessing the commercial value of forests and the quality of soils, respectively. They need, however, to be expanded over non-managed forests, adapted for carbon cycle studies, and be made available on a georeferenced basis*
- Inventories of dissolved carbon in the main ocean basins, measured at 5 to 10-year intervals, to estimate the sequestration of anthropogenic CO_2 into surface waters.
- ➢ *These observations are currently made by the research community; they need to be systematized, carefully intercalibrated, and expanded over poorly sampled ocean gyres, and, most importantly, they need to be made.*

Measuring changes in carbon stocks in these three pools is critical for carbon closure. It is a fundamental check upon the system, and essential for hindcast reanalysis of the carbon budget.

Processes. The third set of observations in the System are measurements related to important carbon cycle processes. Most of these will remain in the research domain, to be coordinated within the framework of the Global Carbon Project. Two process-related observations, however, are more appropriate for the operational domain and will become part of the core set of the System:

- Fire distribution (hot spots) and burned area extent, to estimate the fluxes of carbon that are emitted during fires. Fire hot spots will be measured on (sub) daily time steps, with fire extent at monthly intervals.
- Land-cover change, to estimate the fluxes of carbon associated with forest clearing and reversion of agricultural lands to natural ecosystems. The sampling interval will be 5 years with a spatial resolution of 1 km.

The observation efforts will be combined with end-to-end data analysis systems to deliver high quality products that will be freely accessible to the scientific, resource management, and policy communities around the world.

Finally, this Report describes the implementation timeline that is designed to build an Operational Global Carbon Observing System by 2015.

2. The Carbon Observation Challenge

The concentrations of CO_2 and CH_4 in the atmosphere are at the highest they have been in the past 25 million years. Current levels of CO_2 have increased by 30% from 280 ppm in pre-industrial times to 370 ppm today, and they continue to rise. Current levels of CH_4 of 2000 ppm are nearly triple the pre-industrial value of 700 ppm.

These changes are caused by human activities; the primary agents of change are fossil fuel combustion and modifications of global vegetation through land-use change (e.g., land conversion to agriculture including pasture expansion, biomass burning, and for methane, the increase in ruminants and rice cultivation). For the decade of the 1990s, an average of about 6.3 Pg C per year as CO_2 was released to the atmosphere from the burning of fossil fuels, and it is estimated that an average of 1.5-2.5 Pg C per year was emitted due to deforestation and land-use change during the same interval.[1]

The increasing CO_2 and CH_4 concentrations in the atmosphere raise concern regarding the heat balance of the global atmosphere. Specifically, the increasing concentrations of these gases will lead to an intensification of the Earth's natural greenhouse effect. This shift in the planetary heat balance will force the global climate system in ways which are not well understood, given the complex interactions and feedbacks involved, but there is a general consensus that global patterns of temperature and precipitation will change, though the magnitude, distribution and timing of these changes are far from certain. The results of general circulation models indicate that globally averaged surface temperatures could increase by as much a 1.5-6 degrees C in a world with an atmospheric concentration of CO_2 twice that of the pre-industrial period.[2]

The increases in greenhouse gases in the atmosphere, as noted, are anthropogenically driven but partly compensated by absorption of CO_2 at the Earth's surface and by chemical reactions in the atmosphere, for example, by the oxidation of methane by the hydroxyl radical.

This Report focuses on CO_2; it does provide, wherever necessary, links to CH_4. A specific strategy is being developed for CH_4 and other non-CO_2 carbon compounds (e.g., volatile organic compounds emitted by terrestrial vegetation) through the Integrated Global Atmospheric Chemistry Observation (IGACO) theme.[3]

Only half on average of the CO_2 from anthropogenic emissions has remained until now in the atmosphere. Analyses of the decreasing $^{13}C/^{12}C$ and O_2/N_2 ratios in the atmosphere have shown that the land and oceans have sequestered the other half, in approximately equal proportions. However, the apportionment of carbon fluxes between ocean and land varies in time and space.

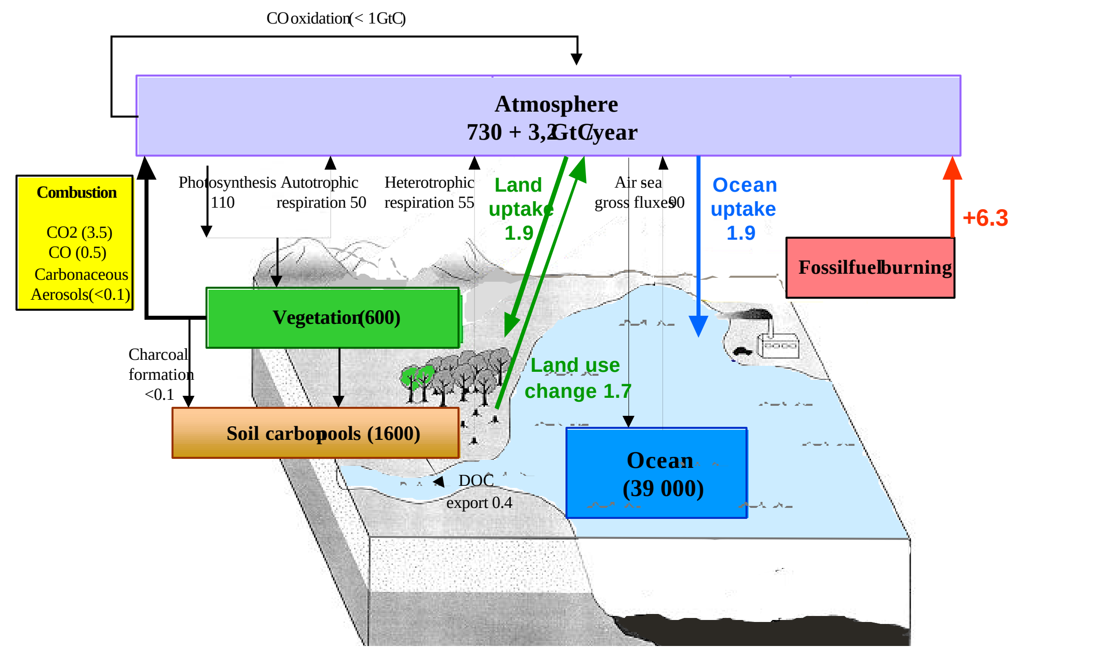
The primary mechanism for current land carbon uptake is most likely the recovery from historical land-use in Europe and North America There are several other terrestrial processes, such as enhanced plant growth due to the increase in atmospheric CO_2, whose effect is not yet well documented. For the ocean, it is ocean circulation coupled with the ocean solubility pump; the role of biota and changes in that role are less understood.

Further, the atmospheric growth rate of CO_2 exhibits large interannual fluctuations, on the order of the average long-term signal. The interannual variability signal cannot be explained by the variability in fossil fuel use. Rather it appears to reflect primarily changes in terrestrial ecosystems induced by changing large-scale weather and climate patterns.

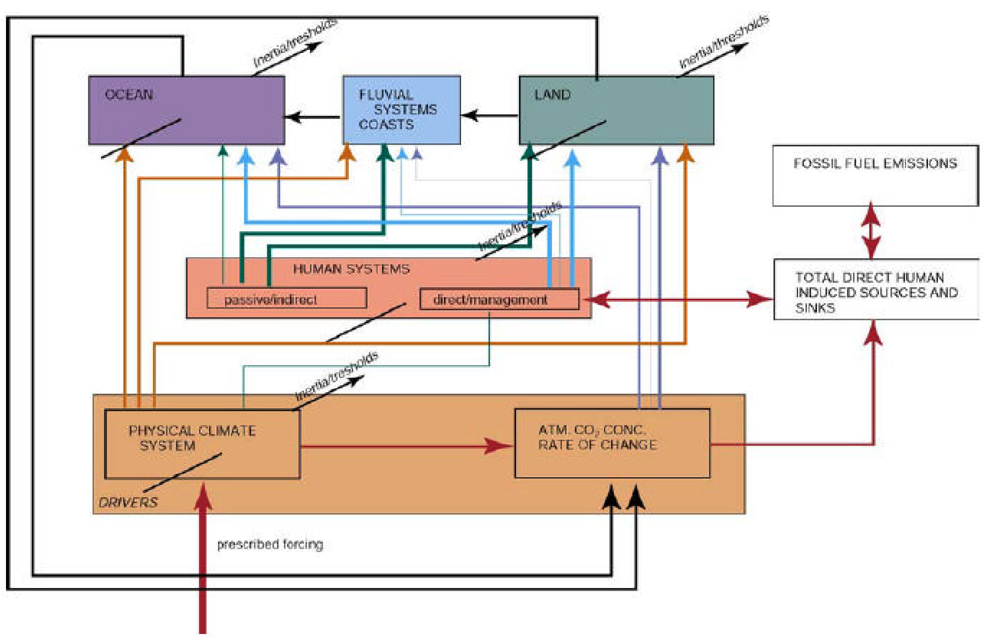
Improved predictions of future CO_2 levels require better quantification and process-level understanding of the present state of the global carbon cycle, including both the natural components and anthropogenic contributions. The current state of the science, however, can neither account for the CO_2 average growth rate nor for the interannual variations with confidence. Such overall patterns of temporal dynamics in the carbon cycle are important, and our understanding of their primary drivers is limited.

At present, limitations in our current understanding also include an inability to locate well key sink or source regions. Independent information on spatial and temporal patterns of CO_2 sources and sinks is of extraordinary value for challenging process-based terrestrial and oceanic carbon cycle models, and thus for our ability to predict future CO_2 trajectories.

Quantifying present-day carbon sources and sinks and understanding the underlying carbon mechanisms are pre-requisites to informed policy decisions. This limitation is fundamental as nations seek to develop strategies to manage carbon emissions and to implement carbon sequestration activities.



The Global Carbon Cycle : (Top) pools and fluxes governing the atmospheric CO2 concentration. (Bottom) Wiring diagram emphasizing how processes in all domains interact to modulate the prospect for effective management



The state of carbon science and its observational foundation must be sufficient to provide robust inferences on the distribution of carbon fluxes and the controlling processes. In part, this knowledge will be based upon existing or developing observational methodologies. For example, the terrestrial flux due to land-use change can be estimated from stock changes (e.g., forest to non-forest conversions); in other cases, remote observations of indicators of primary production (e.g., ocean colour) will guide process and/or phenomena based models. *In-situ* observations will provide essential calibration and quantification information.

Measurements of the atmospheric concentration of carbon dioxide form an effective complement to verify measurements of carbon stock changes and process-level activity indicators. This is because the atmosphere is a rapid but incomplete mixer and integrator of spatially and temporally varying surface fluxes; therefore, observations of the distribution and temporal evolution of CO_2 *in the atmosphere* can provide a powerful gauge of surface fluxes. However, at present, the network of *atmospheric in situ* stations is too sparse to constrain well the pattern of sources and sinks; the density and coverage of the network could be increased to improve the flux estimates.

New techniques are urgently required to fill significant gaps. The most important of these is the satellite measurement of the distribution of global atmospheric CO_2, which is able to densely sample the atmosphere and capture atmospheric CO_2 gradients directly over source/sink regions. These global observations provide the essential independent constraint on models of surface fluxes and the underlying processes. This complement is the key to answering critical questions regarding spatial and temporal variability of carbon sources and sinks, and it forms the crucial capstone of the integrated observational strategy.

The ultimate target spatial resolution for global carbon dioxide fluxes is 10 km over land and 50 km over oceans with temporal resolution of a week. This can be attained with the expected full Operational Global Carbon Observing System (Section 4) and with significant improvements in data assimilation, atmospheric transport models, and *in situ* process models. The shorter-term objective of monthly fluxes with spatial resolution of 100 km over land and 500 km over the ocean should be possible within the decade (Section 5). Finer spatial resolution (10 km), however, might be attainable in some situations in the short-term for mechanistic studies and verification of compliance with policies.

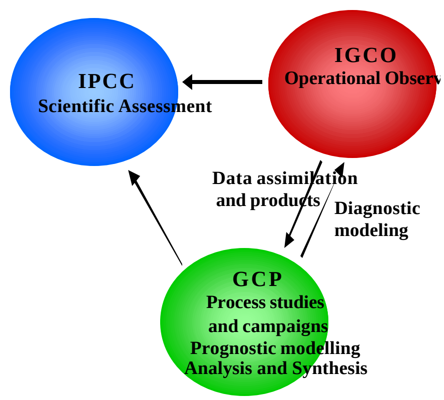
In summary, an Operational Global Carbon Observing System would contribute to answering critical scientific and societal questions. Those questions include:

- What are the size, location, and processes controlling present-day terrestrial and marine carbon sources and sinks?
- What is the effectiveness of deliberate sequestration activities? What are the implications for the global carbon cycle of these activities?
- What will be the behaviour of carbon sources and sinks in the future under higher CO_2 and possibly altered patterns of

climate, land vegetation, and ocean circulation?

3. The International Context

The challenge of understanding and managing the carbon cycle can only be met through a coordinated set of international activities – research, observations, and assessment. All three are essential, tightly linked activities, which depend upon one another to achieve an overall understanding and knowledge base.



Links between IGCO operational observation, Research planning (GCP) and assessment (IPCC)

Research. There is an extensive array of individual and national carbon cycle research activities. At the international level the International Geosphere-Biosphere Programme (IGBP),[4] the International Human Dimensions Programme on Global Environmental Change (IHDP),[5] and the World Climate Research Programme (WCRP)[6] have recently joined forces to build an international framework for integrated research on the carbon cycle, the Global Carbon Project (GCP).[7] The GCP's three major themes are:

- **Patterns and Variability:** the current geographical and temporal distributions of the major stores and fluxes in the global carbon cycle.
- **Processes, Controls and Interactions:** the underlying mechanisms and feedbacks that control the dynamics of the carbon cycle, including its interactions with human activities.
- **Future Dynamics of the Carbon Cycle:** the range of plausible trajectories for the dynamics of the carbon cycle into the future.

The relationship between the Integrated Global Carbon Observing theme and the GCP is particularly important, with GCP providing a framework for model development and intercomparison, advanced process studies, and research-based observations; and Integrated Global Carbon Observing theme providing a strategy and implementation plan for systematic, long-term observations of carbon fluxes, pools and processes.

Observations. Coordinating key global observations needed to improve understanding of the carbon cycle falls under the broad Integrated Global Observing Strategy (IGOS)[8] that seeks to unite the major satellite and surface-based systems for global environmental observations of the atmosphere, oceans, and land. The development and implementation of the IGOS is through a partnership, IGOS-P, among space agencies, as represented by the Committee on Earth Observation Satellites (CEOS)[9]; the Global Observing Systems (the Global Ocean Observing System (GOOS),[10] the Global Terrestrial Observing System (GTOS),[11] and the Global Climate Observing System (GCOS)[12], as represented by both their programme offices and their sponsoring agencies; and the research community, as represented by two major international research programmes, IGBP and WCRP, under the scientific sponsorship of the International Council for Science (ICSU). The sponsoring agencies of the Integrated Global Observing Strategy include several organisations of the United Nations: the Food and Agriculture Organisation (FAO), the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific and Cultural Organisation (UNESCO); the United Nations Environment Programme (UNEP) and the World Meteorological Organisation (WMO). The financial sponsor of the research programmes, the Internal Group of Funding Agencies (IGFA), is comprised of the national research councils, science foundations and other significant funding bodies of the major countries involved in global change research.

The Integrated Global Carbon Observation theme team has the task of formulating, within the IGOS context, a strategy for building an operational global carbon observing system, encompassing the ocean, the land and the atmosphere, and including *in situ* as well as remotely-sensed observations. Key to this is the ability to integrate carbon observations from a wide variety of platforms and techniques within a coherent modeling framework based on data assimilation and model-data fusion methods. The Integrated Global Carbon Observation theme team is closely related to and benefits from the Terrestrial Carbon Observation (TCO) initiative, a component of GTOS, which has developed an extensive framework and implementation strategy for a comprehensive terrestrial and atmospheric carbon cycle observing system.

The Strategy for developing an Operational Global Carbon Observation System rests similarly upon a strong base for ocean carbon observations, and benefits from the GOOS report N°118 that provides a strategy for a global ocean carbon observation system and its connectivity to the atmosphere.

Furthermore, ocean carbon survey will be linked with 10-year repetitive transects being planned in cooperation with CLIVAR. There is also an initiative to develop a Global Time Series Observatory System pilot project, consisting of a limited set of mulit-disciplinary sites is being considered **Reference Needed**. Finally, there is an important technology challenge to develop observing systems for *in situ* carbon, such as an inexpensive carbon micro-sensor to be implemented on ARGO floats .

In addition to the existing global-scale but compartmentalised observation strategies, there are a number of important regional and national observation systems and strategies that will contribute valuable components to the strategy for developing an Operational Global Carbon Observation System.[13] At present, however, they still operate in a fragmentary fashion and their full potential can only be realized through the development of an internationally integrated observational strategy, as envisioned in Section 4. All of the building blocks are described in more detail in Section 5.

Finally, the strategy is strengthened through close collaboration with the Global Carbon Project on the development of model-data fusion methodologies.

Assessment. For the carbon cycle, the primary assessment activity occurs through the work of the

Intergovernmental Panel on Climate Change (IPCC). For example, the IPCC's Third Assessment Report (TAR) produced a comprehensive and well documented synthesis of our current understanding of carbon cycle dynamics. Special reports of the IPCC on Emission Scenarios, on Land Use, Land Use Change and Forestry activities, and Special Guidelines for sources and sinks reporting have also been produced to assess the scientific basis for carbon sequestration under the Kyoto Protocol. The IPCC has launched two additional assessment activities related to the carbon cycle: a special report on Carbon Dioxide Capture and Storage, due to be completed in 2005, and a collaborate effort with the research community to understand better the mechanisms that are leading to the current terrestrial carbon sink, and the direct and indirect human influences on this sink.

4. Towards an Operational Global Carbon Observing System

The aim of this section is to outline briefly the Global Carbon Observing System as it is envisaged when it is operational, by 2015. Section 5 will provide more detail as to how this fully operational system can be built from a combination of existing components and the development of new components. Several aspects of the evolution to a fully operational system are important. First, the transition from research observations to operational observations (monitoring) is a critical step for most components of the Operational Global Carbon Observing System. Second, to meet its objectives, the System must integrate operational observations with models, and since model development and implementation is a primary responsibility of the Global Carbon Project (GCP), close collaboration between the GCP and the observing system is essential. Finally, the carbon cycle is closely linked to other biogeochemical cycles, to the physical climate system, to terrestrial and marine ecosystems, and to a range of human activities. Thus, the spectrum of measurements of relevance to the carbon cycle is potentially vast. The strategy of the Operational Global Carbon Observing System is to focus on a **core set of operational observations** that are centrally important for the carbon cycle itself.

4.1 Scope and Objectives

The Operational Global Carbon Observing System has two principal objectives:

- To provide the long-term observations required to improve understanding of the present state and future behaviour of the global carbon cycle, particularly the factors that control the global atmospheric CO_2 level.
- To monitor and assess the effectiveness of carbon sequestration and/or emission reduction activities on global atmospheric CO_2 levels, including attribution of sources and sinks by region and sector.

The first objective has both basic research and policy components, while the second is aimed at providing policy makers with direct and useable information in the context of international negotiations to regulate greenhouse gas emissions.

By combining reliable and well-calibrated measurements with realistic models of the marine and terrestrial carbon cycle one may infer, by means of inverse modeling and data assimilation, constraints on the fluxes of CO_2 between the Earth's surface and the atmosphere and thus address both objectives. This integration of models and data requires establishment of both data requirements and modelling-assimilation strategies.

4.1.1 Data Requirements for Integration

Well-founded data requirements must be established to provide a rationale for new measurements, the development of new technologies and advanced algorithms, data harmonisation, archiving and distribution. Until now, the majority of carbon observations have been tailored for research purposes, supported by research funding agencies and implemented mainly through national research programmes. This global-scale research effort will now be coordinated internationally by the Global Carbon Project. The challenge is to move towards a more focused, systematic system for monitoring carbon sources, sinks and processes, built around a backbone of core operational observations designed to meet the Global Carbon Observing System objectives. Although research-generated observations will continue to be important, the most urgent priority is to implement, expand and enhance the core set of operational observations. A summary of the required observation system is given in the boxes in this section, classified into core and ancillary observations. A Roadmap for achieving these observations is presented in Section 5.

4.1.2 Modelling Strategies for Integration.

Models validated by rigorous tests and supported by observations are a critical element for synthesising the spectrum of carbon observations, as already clearly recognised by the GCP, TCO and GOOS.

Models can assimilate a wide range of routine observations, allow the use of imperfect or proxy measurements, help fill gaps in time or in regions of incomplete coverage, and provide a quantification of errors. A summary of model types and applications is given in Section 9. Models further enable us to invert observations into the desired carbon cycle quantities, such as surface sources and sinks or key driving parameters that may not be directly measurable or are unobservable at a particular scale. In addition, models can encompass the wide range of spatial and temporal scales needed to quantify carbon pools and fluxes; they thus provide an efficient means for optimising the design of cost-effective observational strategies.

The current challenge is to apply a multiple constraint approach using state of the art carbon models coupled to climate models, assimilating both *in situ* measurements and remotely sensed information. As an example, the operational oceanography community (via GODAE) have launched in the last decade a suite of global observing instruments in space, including altimetry, and to sample intermediate and deep waters, are launching up to 3000 ARGO autonomous profilers. In parallel, data assimilation schemes have been developed, aiming towards an operational system in 2005 at global and regional scales. This kind of approach that provides both nowcasting (real-time analysis) and hindcasting (decadal reanalysis) must be envisioned for the carbon-climate system.

A major research focus of the Global Carbon Project is to carry this concept forward in order to understand and interpret the present behaviour of the carbon cycle, to simulate future CO_2 levels and, ultimately, to contribute to the projections of future climate change. The challenge for the Operational Global Carbon Observing Strategy is to realize the high quality, consistent, long-term data to support the models, while maintaining enough flexibility to respond to new observational challenges as understanding of carbon cycle dynamics evolves. Key issues for integrating systematic carbon observations in models are presented in Section 6.

4.2 The Operational Global Carbon Observing System

The Operational Global Carbon Observing System needed to address the dual scientific and policy-relevant objectives stated above depends on both the research and operational agencies. It is designed primarily to monitor **fluxes** to the atmosphere, and within carbon reservoirs, and **pools** of carbon on a long-term basis and to contribute to the observational base needed to understand the dynamic **processes** that control the carbon cycle It focuses on long-term operational measurements, while aiming to build the partnerships needed to engage research-based observational networks and models appropriate for data assimilation.

4.2.1 Fluxes: Magnitudes and Distributions

The highest priority for the Operational Global Carbon Observing System is to generate global, high resolution maps of the CO_2 fluxes between the Earth's surface and the atmosphere. The fundamental components of any carbon flux-measuring system must be *in situ* and space-based **atmospheric measurements** of the CO_2 distribution, as the atmosphere directly reflects the human perturbation of carbon cycle dynamics (primarily the combustion of fossil fuel and land-use change) and is a sensitive indicator of the exchange of carbon between the atmosphere and the oceans and land. Satellite measurements of atmospheric CO_2 distribution will be integrated with ***in situ* surface measurements** (e.g., ocean dissolved and marine boundary layer pCO_2, eddy covariance measurements of ecosystem-atmosphere fluxes), scaled up using appropriate remote sensing data of surface properties with global coverage. The surface data will be assimilated within a modelling framework or used to calibrate or validate the remotely-sensed observations of atmospheric CO_2 distribution. The remotely sensed atmospheric observations that are foreseen will have a spatial resolution of 10 km or finer and near repeat interval of one week or less (for a typical polar orbit, this is obviously latitude dependent).

Combined together, *in situ* flux measurements, remote sensing data streams, including space-based atmospheric measurements of CO_2, and model analysis will deliver by 2015 global flux distribution at a spatial resolution of 10 km over land and 50 km over the oceans and a temporal sampling of about a week.

Box 1 : Determining carbon fluxes between the atmosphere and the Earth's surface

Observations toolbox

Core Observations

- Atmospheric column CO_2 concentration measured from satellites, with ground-based quality control
- Atmospheric CO_2 concentration measured from *in situ* networks, including airborne
- Land-atmosphere CO_2 flux measured via eddy covariance flux networks covering all ecosystems / regions
- Basin-scale observations of the air-sea flux (ocean pCO_2) from ship-based measurements, drifters and time series as well as variables needed to calculate fluxes (e.g., SST, wind)

Ancillary Observations

- Global, synoptic satellite observations to extrapolate point-wise *in situ* data to larger scales

Modelling toolbox

- Top-down atmospheric transport models to invert fluxes from concentrations
- Bottom-up ocean and land carbon models, both diagnostic and prognostic, to integrate space-borne and *in situ* data into global flux products

The flux observation components of the System are given in Box 1.

For *in situ* measurements over land, high spatial and temporal resolution is required to account for the heterogeneity in land cover and to connect land management practices (e.g., farming, forestry) to the exchange of CO_2 with the atmosphere. **Eddy Covariance** techniques now allow continuous monitoring of CO_2 fluxes over vegetation canopies. Terrestrial fluxes and their variability must be connected to weather patterns and biological processes. Temporal resolution of a week or so is sufficient to capture the variability in terrestrial fluxes driven by changing weather patterns (e.g., the effect of frost or drought on forests).

Over the oceans, CO_2 fluxes must be firmly related to physical and biological parameters (see Section 4.2.3) in order to map fluxes correctly. Observations of **surface pCO_2** at approximately monthly intervals over basin scales are required to make estimates of air-sea fluxes. The Operational Global Carbon Observing System must also accommodate the significant variability of the fluxes in areas like the coastal margins and estuaries, where large gradients in water properties and productivity occur. This requires that the System must have the capability to support sampling at higher spatial and temporal resolutions, and to include ancillary observations that inform about underlying processes. The Operational Global Carbon Observing System must also provide estimates of horizontal, sometimes called lateral, fluxes, even if these do not imply any net loss or gain to the atmosphere. **Lateral fluxes** include carbon transport by erosion, river transport, and wood and food product trade (see Section 5.3).

Finally, the Operational Global Carbon Observing System must be able to detect improbable but potentially large carbon fluxes, such as CO_2 or CH_4 from destabilization of permafrost areas or hydrates at the continental shelf margins. For the latter, collaboration with the proposed observing system for atmospheric chemistry (e.g., IGACO) is essential.

Models are required to extrapolate from local flux measurements to global flux maps (see Box 1). Two types of model are particularly important: i) atmospheric transport models are required to invert atmospheric observations of CO_2 distribution into flux fields; and ii) carbon cycle models are required to assimilate the wide range of *in situ* observations of fluxes and ancillary measurements.

It is important to recognize that none of the surface flux-measuring components of the Operational Global Carbon Observing System currently exist in the operational state. The biggest challenges in building this component of the System over the next 15 years are therefore i) to develop and deploy the technologies that enable remote sensing from space, surface and aircraft of column atmospheric CO_2 concentration and ii) to expand and enhance both the current *in situ* flux measuring research networks and transform them to operational systems.

4.2.2 Pools: Magnitudes, Distributions and Changes

In addition to mapping surface-atmosphere fluxes, the Operational Global Carbon Observing System will determine changes in the distribution and magnitudes of key carbon pools and their evolution over time (Box 2). Measuring changes in carbon pool sizes requires a temporal sampling period much longer than that required for fluxes. Indeed, given the heterogeneous nature of most carbon pools and the fact that anthropogenic perturbations are generally much smaller than the total carbon store, only changes over several years can normally be detected.

Over land, the Operational Global Carbon Observing System will make repeat measurements (5-year intervals) of **above-ground biomass** in sample plots in all major forest biomes including both unmanaged and managed forests in the tropics, the temperate and boreal zones. Accounting for the fate of carbon in wood products is necessary to close the budget of biomass inventories. The strategy is to collaborate with national forest inventory programmes; the primary challenge is to harmonise the data from various countries, to adapt them for carbon cycle studies, and to report them in a transparent and verifiable manner to form an internally consistent global dataset for carbon accounting purposes and other scientific studies. Space-based measurements of biomass are also highly desirable; these depend critically on development and deployment of satellite lidars (e.g. Vegetation Canopy Lidar) and the appropriate radar systems (long wavelength radars and/or polarimetric interferometry).

Similarly, **soil carbon** survey programmes, developed in synergy with plant biomass inventories, will detect long term changes (each 5-10 years or so depending on local spatial variability) in carbon accumulation in soil horizons. However, given the huge heterogeneity of soil carbon distributions, numerous sampling sites around the world will be needed to detect significant changes in pool size.

Over the main ocean basins, measuring **the ocean dissolved carbon** pool approximately every five to ten years will be sufficient to corroborate independently the air-sea flux mapping efforts. Determination of carbon pool sizes is of special interest for particular oceanic domains, such as the deep-water production areas in the North Atlantic and the Southern Ocean. Existing multi-tracer techniques will be refined to correctly estimate the invasion of the excess of atmospheric CO_2 into the ocean against the high background of natural dissolved inorganic carbon. The potential GEOTRACES (**Need web site**) program would address well the *in situ* ocean carbon measurement requirements.

Box 2 : Monitoring carbon pools and pool changes

Observation toolbox

Core Observations

- Forest biomass inventories over all forest biomes
- Soil carbon inventories

Basin-scale *in situ* measurements of dissolved and particulate organic and inorganic carbon the ocean , with full column sampling of carbon system parameters

Ancillary Observations

- Carbon storage in the sediments of reservoirs, lakes
- Carbon storage in anthropogenic pools, primarily wood products
- Sediment trap and sea-floor studies, with a special emphasis on coastal sediments

Modeling toolbox

- Carbon process models that include transfer and cycling into fast, intermediate and slow

Finally, ancillary observations will be made of carbon storage in reservoirs and lakes and in carbon product pools (both wood products and food products including their processing and displacement in trade systems, storage due to charcoal formation, and storage in the deep sediments in the oceans. In particular, better measurements of the amount of carbon buried in coastal sediments will be obtained to improve estimates of the amount of carbon exported to the deep ocean via rivers.

The pool measurements undertaken by the Operational Global Carbon Observing System will enable key fluxes among sub-pools *internal* to each reservoir to be measured, in addition to the fluxes between the surface and the atmosphere. In particular, processes which transfer carbon from fast pools in contact with the atmosphere (e.g. the ocean mixed layer, leaves) to pools of longer turnover times (e.g., ocean intermediate waters, trunks and litter) need to be monitored closely.

Of the core measurements for carbon pools outlined above, only forest biomass inventories (and in some cases soil surveys) currently exist as operational systems, but not with the purpose to evaluate carbon storage, rather commercial values of trees (or soil erosion and fertility). However, these are entirely nationally based, so the harmonisation of existing data and the standardisation of methodologies is a central issue. All other pool measurements exist only in research mode, and considerable further development is required before they can be included in hind-casting, re-analysis, or carbon budget studies in the context of an operational system.

4.2.3 Linking fluxes to processes by observations

One of the three major themes of the Global Carbon Project is to develop a better understanding of the processes that drive the dynamics of the carbon cycle. Improvement of process-based carbon cycle models is a key element in the GCP strategy. Because models are developed and tested on the basis of measurements of carbon cycle behaviour, process relevant observations are an important part of the strategy. For example, observed flux patterns give vital information on underlying fundamental processes (e.g., air-sea gas exchange, primary productivity of the ocean and land, photosynthesis, respiration, fossil fuel emissions, biomass burning).

Nearly all of the measurements used in model development lie in the research domain and will remain so for the foreseeable future. However, two observations are especially important, both to estimate fluxes and to inform about the underlying processes, and thus are recommended to become core observations in the operational domain. First, land-cover change is responsible for significant emissions of CO_2 every year, usually estimated to be in the range 1.5 - 2.0 Gt C y^{-1}. Routine observations of land-cover change, with global coverage at a resolution of at least 1 km. globally, will constrain this important flux much better and will also provide insights as to the drivers of the observed changes. Second, ecological disturbances often lead to event-related, large emissions of CO_2 and other carbon compounds. Globally, the most important disturbance is fire, a source of 2-4 GtC y^{-1},partly offset by ecosystem regrowth after burning. Remote sensing technologies now allow the monitoring of fire distribution and extent of burned areas; such measurements are recommended to become core observations in the Operational Global Carbon Observing System.

Box 3. Linking fluxes to major processes :

Observation toolbox

Core Observations

- Monitoring land-cover change disturbances from space
- Monitoring of fire disturbances from space
- Monitoring other disturbances affecting ecosystem condition (insects, harvest, windstorms)

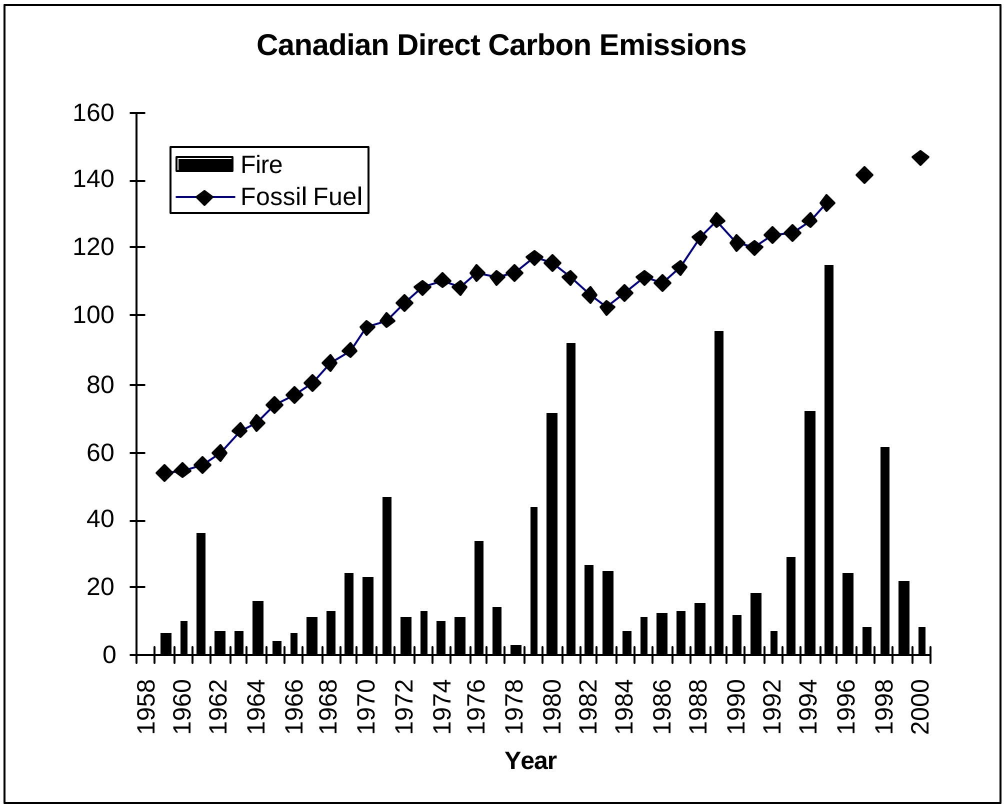
Ancillary Observations

- Co-sampling of parameters related to processes at eddy flux towers (e.g. soil moisture, nutrients, respiration terms, phenology)
- Co-sampling of parameters related to processes from ship-based measurements, drifters and time series (e.g. ecosystem variables, pigments, nutrients)
- Space observations related to processes driving CO_2 fluxes. For instance,
  - *Ocean colour measurements*
  - *Climate and weather data, including precipitation*
  - *Soil moisture content*
  - *Leaf Area Index and related vegetation biophysical properties*
- *In situ* observation related to processes
  - *Soil characteristics*
  - *Phenology of terrestria l vegetation*
  - *Nutrient distributions (ocean and land)*
  - *Species composition of ecosystems*
- Atmospheric tracers to separate ocean and terrestrial sources, fossil fuel and biomass burning (O_2:N_2 ; ^{13}C-CO_2 ; CO ; aerosols).

Non-CO_2 toolbox

- Space observations of wetlands extent for CH_4 natural fluxes
- Observation of non-CO_2 respiration fluxes over ecosystems (BVOCs, CH4…)
- Bottom-up ocean and land carbon process-based flux models to relate fluxes to processes

A large number of ancillary process relevant measurements (Box 3) are important for the development of carbon cycle models. Some of these will remain as research observations and thus within the domain of the Global Carbon Project; others will be made as part of other observational systems, for example, meteorological observations of the physical climate system. Thus, it is important that the Operational Global Carbon Observing System maintain a close collaboration with the GCP, with national research programmes, and develop partnerships with other observation systems (e.g., climate, biodiversity, atmospheric chemistry).



Comparison of fossil fuel CO_2 emissions and fire induced CO_2 emissions of Canada shows the importance of biomass burning in regional carbon budgets

Many of the ancillary measurements will be co-sampled with the operational flux measurements (e.g., as part of research programmes associated with the eddy-flux network or as part of shipboard measurements on research cruises). Several are now routinely measured from space-based platforms and are included in other observation systems; for example, measurement of ocean colour is included as a component of the Oceans Theme of IGOS-P.

The ancillary measurements also include observations needed to determine the net carbon balance of ecosystems, such as knowledge of emissions of non-CO_2 carbon gases such as CH_4, CO, and Non-Methane Hydrocarbons (NMHC).

5. The Challenge to Realizing the Global Carbon Observing System

Figure 5. Airplane of AN-2 type used to sample vertical profiles of CO_2 in the lowest atmosphere over Central Siberia

The current system components are reviewed in Section 5.1 by Earth System domain (atmosphere, land, ocean), and Section 5.2 presents recommendations for expanded observational capabilities. For the atmosphere, there is a particular emphasis on a new space-based measurement instrument. This domain approach reflects the current organization of most of the existing methodologies as well as the research and observational communities. However, the Strategy for realizing an Operational Global Carbon Observing System will shift this existing domain-orientation to a structure based on flux, pool and process-related observations (Section 4).

5.1 Identify the Building Blocks

Building the Global Carbon Observing System outlined in Section 4 requires a pragmatic strategy based upon existing observation systems so far as possible. Identification of fundamental existing components have been carried out respectively by TCO for terrestrial and atmospheric measurements and by GOOS for ocean measurements (see Section 9). These systems and networks provide the building blocks from which an Operational Global Carbon Observing System can be developed. However, at present they are mainly research tools and cannot be considered operational. These observations need significant enhancement, extension, and optimization.

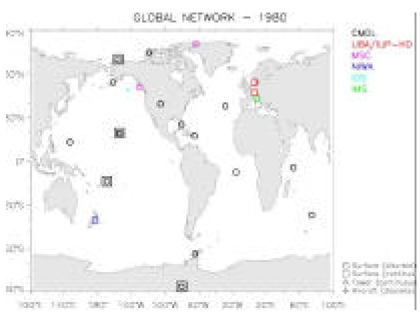
5.1.1 Existing Atmospheric Observations

The atmosphere is a fast but incomplete mixer and integrator of spatially and temporally varying surface fluxes, and so the distribution and temporal evolution of CO_2 in the atmosphere can be used to quantify surface fluxes, using numerical models of atmospheric transport. This process is known as inverse modelling. Relevant atmospheric observations also include carbon tracers and other tracers indirectly useful for carbon studies. Carbon tracers ^{13}C-CO_2, ^{18}O-CO_2 and O_2:N_2 deliver specific constraints to separate terrestrial from marine fluxes. Other tracers, such as inert gas SF_6, or C_2Cl_4 and ^{222}Rn, are used to evaluate atmospheric transport parametrisations in models. Tracers related to combustion CO and black carbon, or surrogates of fossil fuel emissions $^{14}CO_2$ are used to constrain biomass burning and fossil fuel emissions. In addition, information on the dynamical structure of the atmosphere is necessary to interpret concentration measurements.

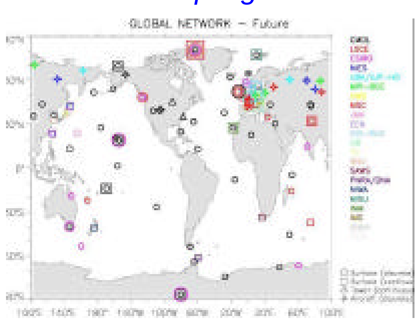
The existing components of atmospheric carbon observations are:

- Flask sampling networks including about 100 sites globally with weekly sampling frequency.[14] In most cases, multiple species are determined from flask air samples (e.g., ^{13}C-CO_2, ^{18}O-CO_2, O_2:N_2, CH_4, N_2O, SF_6, CO).

- Continuous stations of *in situ* CO_2 monitoring, including several marine atmosphere baseline stations (e.g., Mauna Loa), mountain stations, and more recently several tall towers in the interior of continents. About 10 of the *in situ* CO_2 stations out of a total of 20 around the globe have long records spanning over the past 20 years.
- Aircraft vertical profiles at about 10 sites around the globe (e.g., North America, Europe, Siberia, South Pacific) which deliver information on the vertical structure of tracers, related to source distributions of CO_2 and to atmospheric mixing.



(Top) Map of Global air sampling network in 1980 (Bottom) Map of near future Global air sampling network

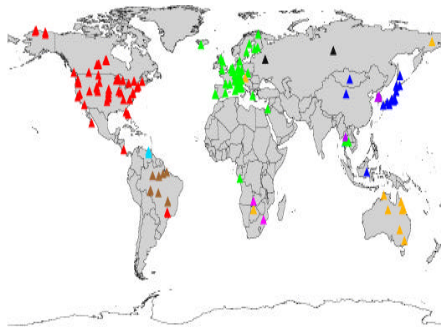


- Calibration and inter-comparison activities. International exchange of standard samples is coordinated internationally by the Global Atmosphere Watch Programme of the WMO for CO_2 and by the International Atomic Energy Agency for isotopes. In parallel, there are several ongoing inter-comparison projects among the major air sampling networks (e.g., through common sampling at the same location).

5.1.2 Existing Terrestrial Observations

The current terrestrial carbon observation base is made up of *in situ* ecological measurements that are generally labour intensive and expensive (e.g., net primary productivity, biomass or soil carbon), flux measurements by the eddy-covariance technique, completed by atmospheric CO_2 concentration at continental locations (e.g. tall towers, aircraft), and remote sensing data and products.

In addition, we have partial information on nutrients, climate, soil moisture and radiation, and on some disturbances (e.g., global maps of burned areas and fire hotspots from satellite).



World-wide distribution of eddy covariance towers measuring CO2, water vapour and energy fluxes. 10 years ago, only 5 such towers were operating

The existing components of today's terrestrial carbon observations are:

- Eddy covariance flux networks (about 100 towers, mainly over forests).[15]
- Forest biomass inventories that exist for most developed countries include a very large number of sampling locations, but many forest biomes have little or no inventory data.[16]
- Soil surveys which exist at regional, national and global scale; however, their utility for carbon studies and particularly for estimates of change in carbon stocks is open to question.[17]

- Networks and transects for ecological studies and phenological observations
- Satellite Remote Sensing (land cover and land cover changes induced by land use practices, vegetation phenology and biophysical properties, fires, radiation).

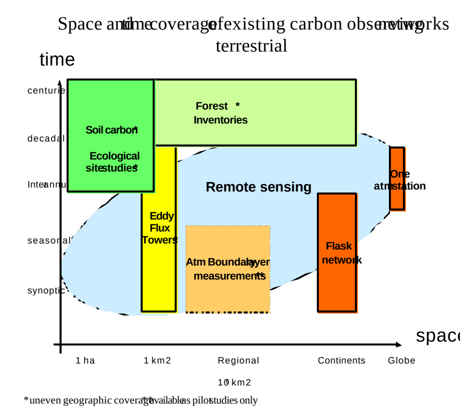
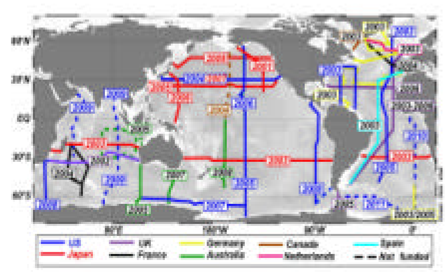


Figure 3. Spatial and temporal coverage of existing terrestrial carbon observations

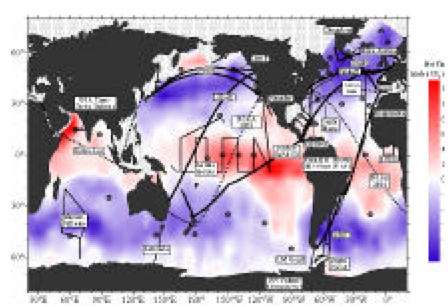
5.1.3 Existing Ocean Observations

The existing components of an ocean carbon cycle observing system are:

- Basin-scale surface observations of atmospheric and oceanic pCO_2 and related parameters on research ships and Ships of Opportunity. Regional datasets have been collected for the North Pacific, North Atlantic and equatorial Pacific. Global data products of monthly air-sea flux maps have been generated using the available pCO_2 data.[18]
- Large-scale ocean inventories from hydrographic survey cruises with full water column sampling of carbon system parameters. At present there are surveys on a 5-10 years time scale since WOCE (the World Ocean Circulation Experiment).
- Moored and shipboard time series measurements of the ocean carbon cycle components. In addition, some stations include sediment traps and sea-floor studies to investigate the transfer of carbon from the surface waters to deeper and longer-term storage compartments in the ocean. There are presently about 30 time series stations measuring carbon cycle variables.
- Satellite remote sensing of parameters related to carbon fluxes (e.g., surface winds, sea surface



(Top) map of existing coverage of ocean repeated inventories (Bottom) map of ocean pCO2 surveys on Ships of Opportunity, moored points.



temperature, ocean colour) as well

as key auxiliary data such as altimetry.

- Coastal Zone time series stations on the continental shelf measuring carbon system variables as part of national research programmes. Many of these are part of LOICZ (Land-Ocean Interactions in the Coastal Zone research project of the IGBP) but are not sufficiently coordinated at the international level in terms of an operational observation network.[19]

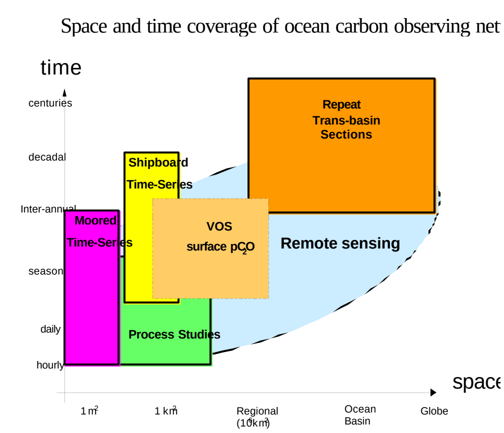


Figure 4. Spatial and temporal coverage of existing ocean observations

5.2 The Major New Elements in the Global Carbon Observing Strategy

One central theme of the Operational Global Carbon Observing Strategy is the integration of satellite observations with key *in situ* measurements.

Satellite sensors measure scattered, reflected or emitted electromagnetic radiation that carries information about surface or atmospheric characteristics. Once calibrated, these measurements can be transformed into carbon cycle variables. Researchers in various programmes and countries have developed accurate and robust algorithms. Coordinated international activities have been undertaken with the sponsorship of organisations such as WCRP, IGBP, CEOS and national space agencies. While much progress has been achieved, this process needs to continue with vigour.

In linking measurements to models, a choice exists as to whether future carbon cycle data models should assimilate carbon cycle variables or be fitted with radiative transfer codes to directly assimilate radiances measured by space-borne sensors. It appears that the latter approach could be better adapted as a means of retrieving fluxes from future satellite CO_2 observations, and could be extended to assimilation of ocean colour and vegetation reflectances.

The Operational Global Carbon Observing System must:

- Support the development and testing of the required algorithms and their modification over time for new sensors. The overall aim should be to acquire and implement community consensus algorithms.

- Support the assimilation of satellite radiances (level 1 data products) using, if necessary, state-of-the-art Numerical Weather Prediction models.

The list of satellite observations that would form the backbone of the Global Carbon Observing System is summarized in Section 9, and is based on a synthesis of the TCO and GOOS reports **add web cites**.

The following four subsections first highlight new satellite technologies for atmospheric CO_2, and the subsequent three sections describe the challenges in enhancing, extending, and optimizing the existing research based observing systems in each domain into operational components of the Global Carbon Observing System.

5.2.1 Space-based Measurement of Atmospheric CO_2

Space-based high-precision measurements of the column-integrated CO_2 molecular density with global, frequent, coverage would be of extraordinary and unique value in determining terrestrial and oceanic CO_2 fluxes. By linking the spatial distributions of CO_2 with atmospheric flux inversions, data assimilation techniques, and coupled atmospheric, terrestrial and ocean carbon modeling (Section 6), the scientific community will be able to determine sources and sinks of CO_2 at unprecedented space and time resolution. In addition, this measurement stream will have value in its independence from *in-situ* measurements or "bottom-up" model-derived estimates of CO_2 flux.

The atmospheric inversion approach exploits the atmospheric gradients in CO_2, which are strongest in the lower part of the atmosphere. In a very real sense, the flux retrieval accuracy is a function of precision and sample density of measured total column CO_2. The measurements need to be at the *0.3% (1 ppm) precision or better* for significant improvements in our knowledge of sources and sinks.

Two spectral domains are usable: the long-wave infrared and the short-wave infrared. Each has advantages and disadvantages.

Using existing measurements in the long-wave from the HIRS-2/AMSU instruments on the NOAA polar satellite series, which were not initially designed for CO_2 retrieval, very promising results have been obtained, producing four years of monthly retrievals at 15^o spatial resolution of the CO_2 concentration over the tropics (20^oN-20^oS) that show good agreement with what is presently known from aircraft instruments[20]. Method-induced error of these retrievals is of the order of 3-4ppm (around 1%). There is promise that additional advances will be achieved by exploiting new long-wave instruments that have been recently launched, such as the Atmospheric InfraRed Sounder (AIRS) - Advanced Microwave Sounding Unit (AMSU-A) package[21] or that will soon be launched, such as the IASI/AMSU[22] suite. The AIRS/AMSU and IASI/AMSU, as well as the planned CrIS[23] have the advantage over HIRS-2/MSU of having a much higher spectral resolution, which allows isolation of a larger set of more specifically sensitive CO_2-channels from the interfering water vapour and temperature signals.[24] A precision on the order of 0.5% at a space-time scale of 100km/weekly is envisaged. These instruments are not being launched with the measurement of atmospheric CO_2 concentration as their focus; however, their capabilities will improve our ability to monitor CO_2 and other trace gases from space.

The disadvantage is that the long-wave measurements tend to capture mostly the upper part of the troposphere, where the signal of surface sources and sinks is of smaller magnitude (except in the tropics) and hence the gradient is weak.

CO_2 monthly mean concentration maps as retrieved from NOAA-10, at the resolution of 15°x15° (1°x1° moving average), for four months corresponding to the minimum (October), maximum (April), or to intermediate values (January and July) of the northern hemisphere CO_2 seasonal cycle.

Figure 7. Modeled uncertainty reduction on surface fluxes as delivered by space-borne CO2 measurements on AIRS (Top) in LWIR and SCIAMACHY (Bottom) in the SWIR spectral domain

Using the short-wave infra-red signal has the advantage of penetrating the atmosphere down to the ground. Retrieval of CO_2 from SCIAMACHY on ENVISAT is underway, using both sun-glint and nadir measurements (the later over land) of the instrument but atmospheric diffusers such as clouds and aerosol particles are an important source of contamination, and, given the 50 km field of view of SCIAMACHY, may yield to high data rejection.

Nevertheless, given the lead time for developing the required sensor technology, better use of existing sensors should be pursued concurrently[25].

On the 2007 horizon, the Orbiting Carbon Observatory (OCO - NASA) will use measurements of reflected sunlight in the short-wave infrared to provide global, high-precision measurements of the column-integrated CO_2 mixing ratio. For the two year OCO mission, the measurement objective is daytime column integral measurements of CO_2 with a precision of 0.3% (1 ppm). This precision is needed to characterize CO_2 sources and sinks. The observatory will carry three high-resolution spectrometers, one for O_2 and two for CO_2 (1.6 and 2.06 µm respectively). It will serve as a pathfinder for future long-term CO_2 monitoring missions.

The Greenhouse gas Observing Satellite (GOSAT - NASDA) is also being planned for launch around 2007, with aims to observe CO_2 global distribution, using either long-wave infra-red or short-wave infrared signals.

Reaching this ambitious goal will require a better characterization of spectroscopic coefficients as well as effects of pressure, water, dust, tropopause location, and other atmospheric constituents. In that respect, the use and development of ground-based solar observatories is urged for CO_2 to characterize the ultimate accuracy of the near IR absorption technique. Such a ground based column CO_2 network will also provide a unique control for any space-based CO_2 mission. Complementary, surface or airborne lidar, used for photochemistry, should be improved to remotely capture CO_2 vertical structure and give insight on estimated CO_2 column bias.

This passive CO_2-focused instrument is a logical next step that builds upon the results from AIRS/AMSU and other spectrometers and interferometers. It does, however, share some of their drawbacks. It may not sufficiently resolve the lower part of the atmosphere, and there is an inherent inability to sample low-light regions.

(a) Artist illustration of the OCO spacecraft orbiting the Earth in Nadir Sounding mode. (b) Landsat image of Hilo Bay, Hawaii illustrating the OCO spatial sampling approach. Ten 1-km wide cross-track samples are collected in each of the three wavelengths at 4.5 Hz along the orbit track.

This could inject a bias into the inferred fluxes since there will be a systemic sampling of photosynthetically active temporal/regional conditions (e.g., day versus night, lack of high latitude samples in the late fall to early spring).

The appropriate next step after OCO is an active mission that focuses upon the measurement of column CO_2 without diurnal, seasonal, latitudinal, or surface restrictions. This mission could be accomplished with the measurement technique based upon Laser Absorption Spectroscopy (LAS),[26] which is a powerful tool for high-precision trace gas spectroscopy. LAS provides measurements of CO_2 via measurements of received power at wavelengths on and off an absorption line.

LAS differs from DIfferential Absorption LIDAR (DIAL) in that DIAL operates in a pulsed mode, which is not required for column measurement.[a] This critical distinction enables exploitation of investment by the commercial telecom industry that have produced highly reliable, multi-watt fibre amplifier product **Fix**adjustable lines that fortuitously operate through a set of clean, well-isolated CO_2 absorption lines.

In parallel to algorithm development and new space-borne sensors,

[a] Determining the atmospheric profile globally of carbon dioxide would be of significant value, but it also presents a very high technological hurdle and would require a very significant investment.

validation and calibration of space-based CO_2 measurements by enhanced *in situ* observations must also be built into the Observing System. Aircraft or balloon vertical soundings must be carried out up to the stratosphere for systematic comparison with remotely-sensed column CO_2 from space, in synergy with network of ground based upward-looking remote sensing CO_2 stations. Efforts should be made to coordinate international satellite observation system projects being planned in US, Japan, Europe and other countries.

5.2.2 Challenges in enhancing, extending and optimizing the *in situ* atmospheric observing system

The first challenge in realizing the *in situ* atmospheric component of the Operational Global Carbon Observing System is to build and stabilize site networks that are denser and more spatially representative of the variability in fluxes. Especially urgent are:

- Expansion of networks over the interior of continents (e.g., Africa, Siberia, Amazon) where the variability of sources and atmospheric transport imposes the need for a much higher sampling density than currently achieved. This expansion may require a range of platforms, including mountain stations, tall towers, tethered balloons, and high frequency aircraft measurements (possibly on commercial aircraft flights).
- Development of multiple chemical-species analysis in flask air samples, including high-precision analysis of tracers (e.g., O_2/N_2, Ar/N_2).
- Improvement of atmospheric tracer transport models and inverse methods towards higher spatial resolution as well as towards better use of prior information on the geographic patterns of the fluxes (e.g., fossil emissions).
- Development of robust remotely-operated continuous analyzers, with an acceptable trade-off between logistical independence and precision, is needed.
- Development of column CO_2 optical sensors in preparation of future satellite CO_2 observations.
- Continuation of intercomparison and calibration activities under the WMO-GAW programme.

A second challenge is to implement these atmospheric observations synergistically with observations on the surface and subsurface, both on land and in the ocean (e.g., on top of eddy covariance towers or onboard ships of opportunity), and to include ancillary observation of ecosystem condition. Atmospheric measurements need to be integrated with surface data into a single, internally consistent, coherent strategy. For instance, tall towers for atmospheric observations should best be located within denser regional networks of eddy flux measurements, ecological studies, and remote sensing information.

5.2.3 Challenges in enhancing, extending and optimizing the terrestrial observing system

The core observations required in the terrestrial domain of the Operational Global Carbon Observing System will be built by expanding and enhancing existing components rather than by introducing new components.

The core observations identified in Section 4 must be transferred to the operational domain over the coming decade. These are (i) the eddy covariance flux networks, (ii) forest biomass inventories, (iii) soil carbon surveys, and (iv) remote sensing of land-cover change and of fire frequency and extent.

Eddy Covariance Flux Network. What is of great importance is to ensure the continuity of existing measurements of eddy covariance ecosystem fluxes for at least 10 years at each site; to expand the network in under-sampled regions and ecosystems undergoing disturbances, develop real time data transfer, and to enhance data quality insurance procedures. Also, calibrated CO_2 concentration measurements should be added on top of suitable flux towers to complement atmospheric networks.

Forest Biomass Inventories. Forest biomass inventories are important for monitoring changes in the above-ground terrestrial carbon pool size. At present, however, these inventories are primarily designed to quantify the volume of merchantable wood in a given region with high accuracy (standard error of 1% at the national level). This quantity relates in a predictable manner to carbon stored in tree biomass. Allometric equations relating biomass to diameter, height and tree age factors are needed to convert these volume estimates into whole tree carbon content. Using constant conversion/expansion factors, as is usually done, results in large errors, since both wood density and expansion factors vary considerably with age and between species. Further, conversion of volume increment obtained from repeated inventories into carbon sequestration needs an extra set of expansion factors that take into account differences in turnover rates of different plant organs.

Eddy covariance Tower near Manaus, Brazil, measuring fluxes of CO2, water vapour and energy

Much work has yet to be done to create continuous, standardised, geo-referenced forest biomass and soil carbon inventories. It is critical to harmonise the widely varying methodologies for inventory and analysis, in order to synthesise carbon estimates based on national forest inventories. In addition, a major observational challenge is to establish allometric functions converting above-ground biomass to total biomass. Further work is also needed to expand the coverage over non-commercial forests and woodlands, over tropical forests, and to develop satellite technology (LIDAR or Radar) for remote sensing of biomass. SAR data are expected to contribute to estimating biomass. However, high resolution observation of forest by SAR has been fragmented in terms of temporal and spatial sense, and conditions of observation (incident angle, etc.) are different from one satellite to another. There is a need to build systematic, repetitive, spatially homogeneous and well coordinated global observation strategies for forest mapping by high resolution SAR.

Soil Carbon Surveys. The soil carbon pool is more than twice the size of both the atmospheric and the above-ground terrestrial carbon pools, and it is extremely sensitive to management practices. In order to characterize this pool, data are needed for both the organic layer and the mineral soil. Carbon concentrations on their own are not sufficient, since the total carbon pool is determined also by bulk density and profile depth. In addition, to understand the vulnerability of soils, it is necessary to distinguish between sub-pools of fast and slow turnover, which are linked to biological, chemical and physical mechanisms of immobilisation.

In many countries separate soil surveys are carried out that allow quantification of carbon stocks in the soil. While most of these surveys suffer from the poor quality of their soil bulk density and stone content estimates, they represent the only source of information currently available. The challenge to the Operational Global Carbon Observing System is to ensure that the current *in situ* soil inventories are standardised, fully exploited and significantly extended. In addition, the system must develop new soil carbon measurement techniques, have the flexibility absorb new model-based approaches for estimating soil carbon, and provide the biophysical parameters needed by models.

Land-use Change and Fire. Two observations associated with processes critical for the terrestrial part of the carbon cycle - land-use change and disturbance - have been included as core observations in the Operational Global Carbon Observing System. The challenge here is to employ in an operational mode satellite systems to monitor land cover changes (5-year time interval, 1 km spatial resolution) , fire hot spots (daily resolution) and burned areas (monthly resolution) The land-cover change observations should also emphasize forest/non-forest transitions at higher spatial resolution (25 m).

The observing system should include, as ancillary observations, improved satellite systems with adequate ground truthing (e.g. at flux tower sites) to provide global coverage of continents on synoptic time scales (1-7 days) for biophysical quantities (LAI, FPAR, and related information such as radiation and soil moisture), in order to estimate photosynthetic activity

Another major challenge for the Observational Global Carbon Observing system is to scale up point measurements and construct a bottom-up, continental scale estimate of the terrestrial carbon budget, with higher resolution information about regional patterns within continents, over seasonal to interannual time scales. This will be achieved by increasing the density of the *in situ* measurements listed in Section 5.1.2 and by increasing the frequency of associated atmospheric sampling, combined with satellite observations.

5.2.4 Challenges in enhancing, expending and optimizing the in-situ oceanic observing system

Some of the ocean carbon observations, such as the pCO_2 surveys, could be transferred from research mode to operational mode in the near future, with significant efforts for enhancing data inter-comparability and reducing instrument maintenance and costs. At present questions about the data quality from an operational system and about the release of data in real-time are slowing the conversion to operational mode. The primary longer-term challenge for developing a global-scale operational ocean observation network is the lack of accurate, robust, cost-efficient, autonomous instruments for surface and subsurface sampling of principle carbonate system components. Conducting sustained observations from dedicated research ships is an essential part of an ocean carbon research programme, but it is labour intensive and expensive. A large-scale operational ocean observation system must be largely built on autonomous instruments. Although several prototype instruments are available, much more research and development is needed to advance the technology to the state of being operational.

A second major challenge for the quantification of global air-sea fluxes is the development of robust algorithms for estimating air-sea gas exchange from easily measured parameters. It is becoming increasingly clear that gas exchange parameterisations based solely on wind speed are not sufficient to constrain the flux to within 20-30%. Additional research is needed to develop algorithms using additional or different parameters (e.g. sea surface roughness) that are more accurate. Once these algorithms have been derived, the necessary parameters need to be incorporated into the observational programme so that more accurate flux maps can be developed.

Ship Of Opportunity used to make routine pCO_2 measurements across the North Atlantic Ocean

Finally, there is a need to develop satellite systems with adequate ground truthing incorporated on ships and buoys to obtain higher ocean coverage of Sea-Surface Salinity (SSS), Sea-Surface Temperature (SST), Sea Surface Height (SSH), wind speed, and ocean colour. (60% global, over a 3-5 day timeframe ***add ref.***). This will serve to extrapolate surface pCO_2 measurements across full basins. Although many of the individual components of such a system exist, a new emphasis is required to build a coordinated system from these pieces.

5.3 Filling Other Gaps in Current Carbon Observation

Other gaps in knowledge hinder the development of a comprehensive observation system for the carbon cycle. While these gaps may be in areas of quantitatively smaller carbon fluxes, they are nonetheless important. For instance, lack of quantitative knowledge about these fluxes could bias the pattern of carbon fluxes and associated processes determined by assimilation procedures. Each subsection concludes with recommendations on observational elements which should be included in the overall strategy, either as ancillary observations or as data to be obtained from other observation systems (e.g., climate, atmospheric chemistry).

5.3.1 Transport through Rivers, Estuaries, and Coastal Seas

Part of the carbon fixed on land is transported to the oceans by rivers, about 1% globally, much more regionally. Although this transport of carbon is well known in principle, it is poorly quantified. The fraction of carbon that takes this pathway varies with the type of soil and vegetation, the season and the hydrological cycle; it is also significantly modified by land management, reservoirs, and dams, and land use practices in watersheds and river basins.

Figure 6. Ocean color pattern off the east coast of the United States in spring (CZCS imager)

To be replaced by MODIS image

River carbon is found in both organic and inorganic forms, and can produce substantial CO_2 and CH_4 fluxes to the atmosphere. Once in the ocean, river carbon is integrated into oceanic carbon cycle processes. Its residence time in the ocean depends on its chemico-physical form and on how far it is transported before it is exhaled back to the atmosphere or buried in sediments. It is now recognized that estuaries play a key role in outgassing substantial amounts of river carbon before it reaches the coastal waters. Transport away from the coasts varies with topography and the local oceanic currents and ranges from a few kilometres to thousands of kilometres, and from a few hours to few hundred years. In addition to river carbon, the specific topography of the coastal ocean leads to enhanced vertical ocean mixing and marine productivity, both of which affect the air-sea flux of carbon in ways that are highly heterogeneous and poorly quantified. Satellite data of ocean colour show that marine biomass is 10 to 100 times larger along the coasts than in the open ocean. Such information for the air-sea flux of carbon in the coastal zones cannot yet be retrieved. River transport of nutrients (N, P, Si) into ocean waters can also have a substantial impact on the coastal ocean carbon cycle. Eutrophication has been recognized for years but its effect on the marine carbon cycle is still poorly understood.

It is important to compile and update existing global databases of riverine dissolved carbon and nutrient transports. In parallel, a high priority is to develop gridded erosion models to spatially allocate the source of the riverine dissolved and particulate organic carbon, and to account for sediment burial in reservoirs and coastal shelves. Quantification of erosion losses into sediments and onto terrestrial landscape positions also needs to be carried out. Similarly, quantification of the transport of carbon off the continental shelves into the open ocean needs to be determined. The IGBP-LOICZ project is undertaking a global-scale survey of biogeochemical budgets, including carbon emission and sequestration, based on a standardised methodology. A critical next step in the development of the coastal zone component of the Operational Global Carbon Observing System is to determine whether the LOICZ budgeting projects should be moved from the research to the operational mode.

5.3.2 Transport of Wood and Food Products via Trade Circuits

Harvest, trade and utilisation of food and wood products transports large amounts of carbon away from the ecosystems that produced them. The carbon is respired back to the atmosphere everywhere humans process and use it. The amount of carbon harvested from croplands and forests is roughly 2-3 Gt C y^{-1} globally, an amount which partly goes into international trade circuits.

Lateral transports of wood and food products have not been well quantified to date. The decay of harvested wood products in pools of different longevities further bypasses the natural return to the atmosphere by respiration and disturbances, but it is not yet clear if it acts to accelerate or to slow down the turnover of carbon fixed by forests. Globally, carbon displacement by products/trade is important but on a regional basis or landscape basis, it may be an even more significant component of the terrestrial carbon balance. The magnitude of this transport varies with the type of transfer and geographic region. Within the context of the Operational Global Carbon Observing System, standardized methodologies are required to process agricultural and forestry data to obtain credible estimates of the magnitude and temporal trends of lateral anthropogenic transfers, including imports and exports of products and packing material. Such methods should aim at producing gridded estimates of the carbon fluxes involved in the processing, the trade, and the consumption of wood and food products.

5.3.3 Non-CO_2 Components of Ecosystem Respiration

The fluxes of non-CO_2 carbon gases such as CO, CH_4 and NMHCs from terrestrial ecosystems, sometimes called "non-CO_2 respiration" must be quantified in order to fully close the carbon budget for an ecosystem, given that atmospheric methods (eddy-covariance flux towers, atmospheric inversions) in general measure CO_2 fluxes only. In some cases, a significant fraction of CO_2 withdrawn from the atmosphere is released back to the atmosphere in the form of non-CO_2 gases (up to 30% in some ecosystems), creating a local imbalance in the CO_2 budget. Globally, the oxidation of these compounds amounts to a production of 1.3 Gt C y^{-1} in the atmosphere. Non-CO_2 compounds produced by terrestrial (and marine) ecosystems may be of sufficiently short lifetime to be quickly transformed into CO_2 before they reach an atmospheric background station, but this is not the case for CO and CH_4, which have mean atmospheric lifetimes of many years. Eddy covariance techniques measuring CO_2 simply miss these fluxes.

The emission, transport and chemical destruction of non-CO_2 carbon compounds is of primary interest of the Integrated Global Atmospheric Chemistry Observation (IGACO) theme. In practice at the scale of eddy flux towers, it is most efficient to measure simultaneously the emissions of CO_2 and of non-CO_2 carbon gases, either directly with micrometeorological methods or indirectly by models driven by ecological process and meteorological data. At the global scale of atmospheric inversions, state-of-the art atmospheric chemistry transport models are required to compute the atmospheric production of CO_2 from its chemical precursors and to account for this process in the inverse retrieval of fluxes. Thus, close collaboration between the Global Carbon Observing System and IGACO is essential.

An important challenge to the atmospheric chemistry observing system is to develop satellite observation techniques to deliver methane related products: global seasonal distribution of wetlands and global soil moisture measurements in particular.

5.3.4 Nutrient Fluxes to Ecosystems

There is increasing recognition of the key role of nutrients (both stores and fluxes) in constraining both terrestrial and marine carbon fluxes and their future evolution. As data is acquired on core carbon cycle variables, parallel data on nutrients, particularly N, P, Si and Fe, will be urgently needed and is important for the Global Carbon Project to develop better process-level understanding of carbon cycle dynamics. This ancillary data will include production rates (wind and water erosion, fertilisation, fixation), changes in soil stores, export to atmosphere and subsequent deposition on land and oceans. There are substantial anthropogenic nitrogen and phosphorus loadings to groundwater and river systems through leaching from agricultural fertiliser and pesticides. On the other hand, silicate may be retained in freshwater systems due to building of dams and large water reservoirs (silicate is needed by diatoms, which account for a substantial part of oceanic export production of carbon). Anthropogenic atmospheric nitrogen deposition to the coastal seas (NH_4^+) can be of equal importance quantitatively as the direct input through rivers.

5.3.5 Geo-referenced Fossil Fuel Emissions

To understand the perturbed global carbon cycle, it is important to improve the observation of the location and timing of fossil fuel emissions. Present data on fossil fuel emissions are typically obtained from energy production statistics and aggregated on an annual basis at the scale of individual countries; little information is presently available of the detailed space and time patterns of fossil CO_2 emissions. In the developing world, fossil fuel emissions are becoming an increasingly important fraction of total carbon emissions, but emissions of CO_2 associated with more traditional fuel types (e.g., with biomass fuel) are poorly mapped.

The Operational Global Carbon Observing System must measure fossil emissions in the major industrialised areas of the world at the appropriate spatial and temporal scales to be utilised in atmospheric transport models and inversion studies. A realistic requirement is a space scale on the order of 10 km or better and temporal resolution that accounts realistically for fossil fuel CO_2 release patterns, such as daily traffic peaks or the enhanced emission of from power plants during cold weather episodes or heat waves. Similar efforts to map biomass fuel emissions should be undertaken.

5.4 Improving Data Products and Delivery to Users

The ultimate goal of the Operational Global Carbon Observing System is to generate data products that are of value for the user communities. Raw observations are rarely adequate on their own. To create usable products, *in situ* measurements from a variety of sources need to be integrated with remote-sensing observations within a modelling framework. To achieve this, a major challenge is to collect, process and harmonise *in situ* data from diverse sources. At present problems with *in situ* data include, among others, inconsistent parameter definitions, incomplete data, differing spatial and temporal scales and sampling bias in measurements.

***General comment*: ADD HERE POLICY ISSUES:** data access for 200miles coastal zone, forestry, FF emissions …) Other issues include the delivery of *in situ* measurements to models. Some *in situ* measurements are infrequent or require laboratory processing or tedious field work, and would thus only enter into an assimilation procedure once every year or so, perhaps to improve the retrospective analysis of carbon fluxes and pools. Some other *in situ* observations on the other hand, such as pCO_2 on ships of opportunity, terrestrial ecosystem fluxes, or atmospheric concentrations, can be transferred in real time to data centres and delivered to an operational procedure to now-cast carbon fluxes, much in the same way as current meteorological observations.

6 The Integration Challenge

6.1 Integrating across Scales

Today, carbon observation systems have sparse data coverage, but they have reached a sufficient stage of maturity so that regional estimates of fluxes, and other carbon quantities can be set as a feasible objective. Science communities are well established for themes such as eddy covariance flux towers, atmospheric networks, or ocean pCO2 mapping.

Organized, globally oriented, networks exist for flux towers, atmospheric concentrations, soil and biomass surveys, ecological studies, and ocean pCO2, but these all different methods operate at different spatial and temporal scales. Uncertainties in either their upscaling or downscaling prevent us from delivering quantitative global understanding of carbon sources and sinks at the regional scale. To reduce uncertainties in an objective manner, we need strong integration across scales, based on modeling schemes for model-data fusion or data assimilation, which can include observation of different characteristics. In the ocean, the intermediate and deep oceans have to be included as these reservoirs are flushed fairly quickly 1-2000 years. The entire marine system must be considered for any kind of overall budgeting.

Data integration should proceed from the merging, synthesis, and eventual the fusion of carbon observations within process oriented carbon models. It will require comprehensive advanced Carbon Cycle Data Assimila tion Models, that are expected to analyze large amount of data and diagnose on a routine basis carbon quantities, and provide error diagnostics. Given the strong carbon-climate interactions, it is most likely that, Numerical Weather Prediction models fitted with specific modules to compute carbon cycling, will provide the best framework to assimilate terrestrial and atmospheric measurements. Similarly, operational oceanography models that work at higher resolution than current ocean carbon models should be appropriately computing the biogeochemical state of the ocean and the pertaining nutrients and carbon fluxes. Ultimately, a global assimilation in full ocean-atmosphere-land carbon-climate is required jointly for physical and biogeochemical variables. This approach will both improve hindcasts and forecasts of weather, climate, and carbon systems.

Remote sensing products ultimately will deliver several orders of magnitude more information than *in situ* measurements. However, including all type of data within a single assimilation procedure may create the risk that the optimal solution would be excessively dependent on potential biases of remote sensing products. In order to avoid this situation, *in situ* data may be kept aside as precious sources of independent quality assessment in the Carbon Cycle Data Assimilation System. It should also be recognized that a variety of different biogeochemical models based on distinct hypothesis should be used in parallel, rather than one single model.

Source: BOREAS

Figure 8. Example of integration across scales from local to regional in upscaling terrestrial observations

Figure 9. Integration across scales for ocean carbon obsevations

The relevant scale at which it is desirable to quantify fluxes from a global perspective is typically 10-50 km with weekly resolution. Over land, climate and weather patterns acting on carbon fluxes at 10km scales and can be analyzed from Numerical Weather analysis with input data from carbon cycle models. Over the ocean, the scale of 50 km is also the one at which meso-scale eddies can be resolved in operational oceanography models. Carbon processes partly operate differently at even smaller scales, depending on topography, ecosystem distributions, and anthropogenic land use patterns. However on timescales of up to a few years they show a remarkable degree of coherency over larger scales, due to the predominantly similar temporal response to climate and weather.

6.2 Model-data Fusion and Assimilation Schemes

The global carbon cycle is a single entity, with multi-faceted aspects cutting across the three major domains: the ocean, the land surface and the atmosphere. The most successful modeling advances made in the field involve combining simulations with observations for the different reservoirs, because results from one domain often place valuable constraints on the workings of the other two.

The multiple constraint approach is applicable in this context in order to extract from independent (orthogonal) observation a comprehensive diagnosis where the risk of bias will be minimized. Using independent observations will narrow uncertainties in the diagnostic evaluation of the datasets through modeling. It will also quantify by how much each observation helps in the overall picture, and based on this, what type and over which area, new observation can be intelligently be added to the network.

Key to pragmatic implementation of the multiple constraint theory, is data assimilation. Such a framework can be established by coupling carbon models of the different processes (biomass growth, disturbances, marine biological activity and ocean circulation, atmospheric transport…) and running them in an assimilation mode so as to best match the available data. The assimilation procedure guides the model in a dynamically consistent way towards the data within their uncertainties, and, in unsampled areas, the model can be used as a "smart interpolator", to obtain a complete diagnosis, or analysis.

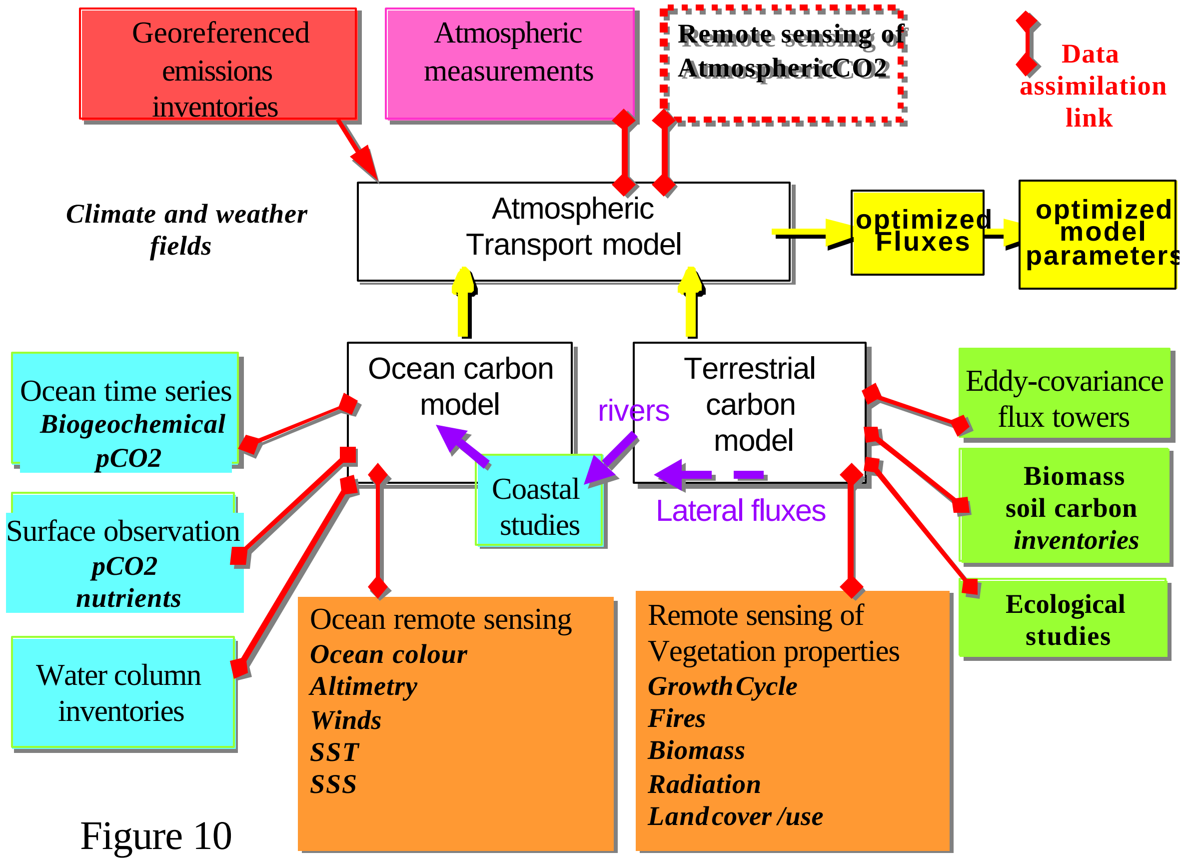


Figure 10. Illustrative conceptual framework and information flow in a global Carbon Cycle Data Assimilation system.

One and useful step further is to go from data assimilation which predicts the state(s) of present and (near)future to data inversion where the observations serve to optimize and to narrow down uncertainties on the model's parameterizations. That way of improving carbon models will no doubt serve to improve future calculations of the long term evolution of the atmospheric CO_2 concentration.

There is no unified model (and likewise no single family of observations), that enables us to understand and estimate the carbon fluxes and their driving processes. Given the diversity of scales, it is possible that a suite or a hierarchy of models nested one within each other might be needed to capture properly the variability inherent to some observations. For instance the CO_2 atmospheric concentration at a tall tower can be interpreted using a suite of nested models from the globe down to proximate source areas. However, the overarching goal of obtaining a global picture of the carbon cycle should be kept in mind, which favors the choice of models that are sufficiently generic in their parameterizations and input variables requirements, and yet based on state of the art mechanistic understanding (see Section 9). We compile below few knowledge challenges specific to the assimilation of carbon observations

A first challenge in building Carbon Cycle Data assimilation systems is their necessary ability to accommodate vast amounts of disparate satellite observations. To best do so, biogeochemical models need to be fitted with radiative transfer modules, in order to let them simulate state variables (e.g. reflectances), which are as close as possible to what the sensors can actually measure. A carbon assimilation system must thereof be dimensioned to digest huge amounts of satellite data, both in terms of variationnal requirements (given non-linearities in the models) and in terms of data processing and storage.

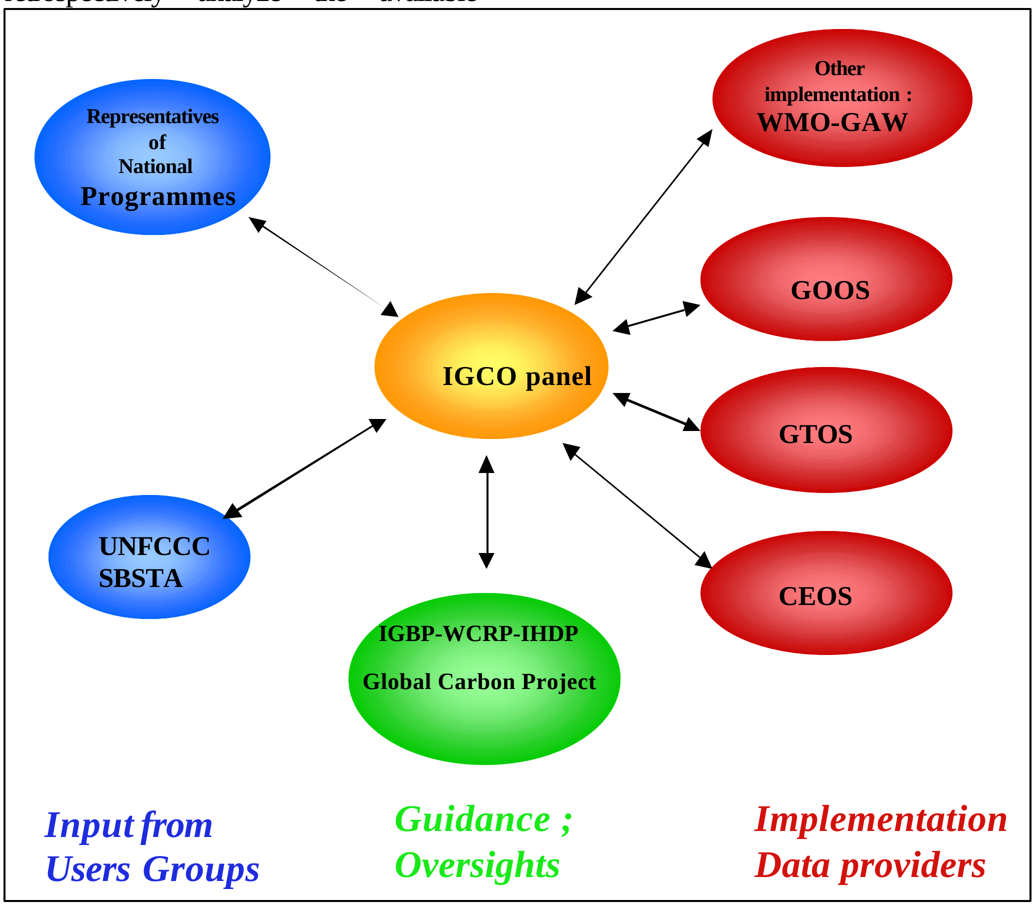
A second challenge is to treat the uneven distribution of *in situ* measurements. Some regions of the world where intensive sampling programs are put in place, are expected to get much better observational coverage than others. Global carbon data integration should thus address the issue of bridging the gap between data rich and data poor areas that should eventually be linked to the atmospheric growth rate and to our ability to mitigate it. Right now, we live in a data-poor world for carbon cycle *in situ* observations, and most of the observations are operated on a research basis. But we see the onset of the development of denser networks with regional emphasis over for instance North America, Europe, Japan, Siberia, the Amazon. It is thus key to the success of a carbon cycle data assimilation system to plan at an early stage improved data calibration, harmonization, and quality insurance procedures which will ensure that in-situ observations produced by different networks are fully compatible one with each other.

A third challenge is to couple weather and climate with carbon cycling. Over land, optimizing photosynthesis will likely alter the latent and sensible heat fluxes, which in turn feedback on the boundary layer transport of atmospheric CO_2. It is thus inevitable that the most realistic manner to assimilate carbon observations is to insert carbon cycling models within Numerical Weather Prediction models, and beyond in coupled ocean-atmosphere-land climate and Earth System models. This will become crucial when remote sensing of the atmospheric CO_2 concentration will be operational, because concentration, temperature and humidity profiles are intimately linked in the atmospheric radiative transfer.

A fourth challenge of assimilating carbon cycle data will be the ability to retrospectively analyze the available observation at regular intervals (say few months). Carbon data assimilation is different in that respect from meteorology where the atmospheric state keeps no memory beyond few days, because there are key long time constants in carbon processes.

7 Institutional and Funding Challenges

The establishment of a systematic observation system for the global carbon cycle is a complex undertaking, primarily because the complexity of the carbon cycle intersects with political and economic structures (e.g., energy systems) that have been established at international as well as national levels. An effective and efficient framework for global carbon cycle observation must rely on several



components, most of which have multiple clients and are sponsored for different reasons. It is therefore essential that the design and implementation of the observing system as well as those of international and national carbon research programmes are clearly linked with each other and to the policymaking community charged with meeting the carbon/climate challenge.

New and stable institutional arrangements are needed in order to establish and maintain these linkages so that a reliable system of observations on the global carbon cycle can be built. A strong and effective partnership with the Global Carbon Project is particularly important to link research and operational observations; to ensure that data produced by the Global Carbon Observing System is fully integrated into model development, analysis and synthesis; and to develop effective protocols for information management.

A particular institutional challenge for the Global Carbon Observing System is to ensure that the component observing systems are coordinated, internally consistent and complementary with respect to space, time and methodological protocol. For instance, there is a need for coordination between the eddy covariance flux tower and atmospheric flask sampling networks. By improving the calibration of atmospheric CO_2 measurements at the top of eddy covariance flux towers, these data can be used in atmospheric inversions. Similarly, improving the accuracy of CO_2 concentration measurements onboard ships of opportunity measuring ΔpCO_2 will help atmospheric methods to improve air-sea flux estimates.

A large challenge to ocean carbon measurement is to coordinate major initiatives involving ship-based, satellite-based, and land-based observation efforts. These are often large-scale, expensive endeavours undertaken with national or regional-based funding. There are numerous opportunities for benefiting from economies of scale arising from international planning and coordination in this realm. For example, in terms of ship-based observations of pCO_2, the CO_2 Panel of the Intergovernmental Oceanographic Commission (IOC) and SCOR (Scientific Committee on Oceanic Research) is collaborating with the Global Carbon Project to ensure the most effective re-occupation of the WOCE hydrograph sections over the coming years.

Thus, it is clear that the Operational Global Carbon Observing System must emphasize coordination and collaboration with existing activities where these are positioned to generate the needed input or output products; use the best available scientific expertise in the generation of new products intended to fill gaps; rely on a small central group (the IGCO Panel) to provide support and continuity for this process; and make extensive use of technological tools such as the Internet, e-mail groups, teleconferences, web-crawling, and database development and maintenance.

Figure 11 presents a proposed framework for the guidance of the Operational Global Carbon Observing System. This institutional structure is designed to meet the challenges outlined above by formation of an Integrated Global Carbon Observing (IGCO) Panel that will be guided by input from its primary user groups and simultaneously interact strongly with the data providers. A key linkage is between the IGCO Panel, CEOS, and the global observing systems (GXOS) that include *in situ* measuring components. Each of these organisations will be responsible for a component(s) of the Operational Global Carbon Observing System, but the System will not be effective without coordination between the components. The IGOS Panel will provide the guidance and oversight required to ensure the appropriate level of coordination.

Equally important is the interaction of the IGOS Panel with the its user groups. The policymakers are represente d at two levels - representatives of the national level policy community and at the level of the UN Framework Convention on Climate Change through their Subsidiary Body on Scientific and Technological Advice (SBSTA). Given the tight coupling between operational observation, research observation and the scientific research itself, the Global Carbon Observing System must have a close working relationship with the Global Carbon Project. This can best be achieved through significant cross-membership of the IGCO Panel and the GCP Scientific Steering Committee; joint activities and workshops; and co-publication of major reports and papers that have both observation and research aspects.

There are two additional organisational challenges towards building the Global Carbon Observing System from national and regional components: i) continuity of observations and ii) research and technology development in support of the observing system.

A major issue confronting the Global Carbon Observing System is to ensure the continuity of the core measurements, at a minimum. Satellite observations are coordinated within CEOS, a partner of IGOS; however, atmospheric *in situ* observations (e.g., trace gas concentrations) are linked via the World Meterological Organization (WMO)[27]to national agencies. Ocean observations are coordinated through the Global Ocean Observing System (GOOS)[28]) in collaboration with national agencies under the auspices of the Intergovernmental Oceanographical Commission of UNESCO (IOC)[29];. For terrestrial ecosystems, the links between the national funding and implementation agencies and the international community are currently weak. Internationally, the Global Terrestrial Observing System (GTOS)[30] and its sponsors (particularly the Food and Agriculture Organisation (FAO)[31], the United Nations Environment Programme (UNEP)[32] and WMO) have national points of contact, but even at the national level, the observation programmes and their funding are not typically coordinated centrally. Thus, one of the biggest challenge s for the IGCO Panel is to gain commitments for continuity in core observations from this exceptionally broad range of organisations, each operating in its own particular institutional setting.

Comment below to be addressed

THAT NO SUGGESTIONS ARE MADE AS TO HOW THIS MIGHT BE ACCOMPLISHED – NOR IS THERE AN IMPERATIVE CALL FOR SPONSORS TO ADDRESS THIS ISSUE WITH PRIORITY. WE THINK A BIGGER DEAL NEEDS TO BE MADE OF THIS NEED!]

Improvements beyond an initial observing system described herein require vigorous support for research development in several areas. The most important of these are: i) improved and new instrumentation for *in situ* and satellite observations of atmospheric CO_2; ii) network enhancement and design optimisation studies, in turn requiring the capability to evaluate trade-offs in performance based on various hypothetical improvements in the observations; and iii) development of models and algorithms that are able to more effectively invert or assimilate raw observations to produce global carbon flux fields.

Implementation Timetable

Phase 1: Preparatory (2003-2006)

- Approval of IGCO plan by IGOS-P
- Improved coordination among existing international programs and components, particularly GCP and IGCO.
- Focused efforts to reduce uncertainties in the current gaps of knowledge in the carbon observing systems (Section 5: Lateral movement of C by fluvial sediment transport, Lateral movement of C by trade and non-CO_2 gases emissions (e.g., CH_4, CO, VOCs). The starting point should be workshops to provide an implementation plan, and obtain agencies commitments for delivering improved estimates of these rather elusive parameters.
- Focus efforts on data analysis and algorithm development to retrieve CO_2 distribution from existing instrument, such as AIRS, SCIAMACHY, IASI and TES, and begin designing an international global carbon cycle satellite observation system combining OCO, GOSAT and European project.
- Begin design of *in-situ* observing system, which will be a precursor of an operational network, assessing how the current observation network should be augmented to include Asia, Australia, Africa, South America and specially the equatorial and southern Oceans (e.g., WMO, NOAA)
- Development of algorithms should be completed to map from Land Observing Satellites (e.g., Landsat, SPOT, ALOS, NPOESS) the global distribution and temporal variability of: Forest-no-forest information; global land use information; biomass information; seasonal growth cycle of vegetation and fires, wetland cover.
- Define a methodology so that global soil carbon content could be updated every 5 years on a 1° by 1° grid
- Define a methodology, including enhanced geo-referenced data availability, so that forest biomass inventory can be updated every 5 years as components of the observing system.
- Design a global network of ecological, bio-optical, and biogeochemical observations, as the basis for calibrating, validating, and adding value to remotely sensed ocean colour data. Products will be the developed through the Ocean Biology Project initiated by CEOS and presently co-ordinated by the International Ocean Colour Co-ordinating Group (IOCCG).
- Evaluate the current capabilities to derive the air-sea gas transfer velocity distribution from satellite measurements of surface roughness (scatterometer and altimeter). Preliminary direct gas

exchange measurements by eddy correlation confirms the general approach, but significantly more process level work needed particularly for high and low wind speed, bubble dominated environments. Scatterometers and Altimeters will surely enhance the operational observing system

- Involve operational satellites agencies such as NOAA, EUMETSAT in these workshops/studies from the very beginning because later they will have to take the lead in this activity;
- Beginning convergence of current regional studies (e.g. CARBOEUROPE, NACP…) to a coordinated program with the Global Carbon Project, which is organizing four "research institutes" in different centres around the world between 2002 and 2005. (The first occurred in May 2002 in Boulder, USA). Each institute consists of 2-4 weeks of talks and practical research training, and deals with data assimilation of one of the three compartments of the global carbon cycle: atmosphere, oceans, and land. The last institute will deal with data assimilation at the scale of the Earth System.
- In parallel to above, we will have focused workshops in Toulouse, Frascati, Tokyo and JPL to assess the quality and accuracy of current satellite data to map column CO_2 distribution from AIRS, SCHIAMACHY etc… and to discuss the data analysis status of Topex-Poseidon and JASON as a model.
- Initiate technology development in the area of Lidars on operational satellites, which may provide a complete profile of atmospheric CO2 and other carbon molecules.

Phase 2: Demonstration (2006-2010)

- Based on the assessment of the status of global carbon measurements coming out of the four workshops organized by CJP ending 2005, we will need to evaluate whether:

- Addition of improved satellite-derived atmospheric CO_2 data sets from dedicated missions, resulting in better flux output products;
- Gradual improvements of Input data products (point and gridded) and of models;
- improving global networks; new inventory data flux estimates are meeting IGCO accuracy and spatial resolution objectives

- Validation of new satellite data of atmospheric CO_2 columns (and possibly vertical profiles) obtained using passive sensors (particularly OCO and GOSAT, but also AIRS, SCIAMACHY and IASI) mission with in-situ network of ground station, tall towers and aircraft soundings.
- End-to-end check on the data system so that it fullfills the need of international modeling community

Phase 3: Pre-operational (2011-2016)

We envisage by this date that the following systems have been established:

- The autonomous surface station global network should be in place, both on land and oceans for a continuous in situ CO_2 analysis with an accuracy of 0.2 ppmv, over the globe with a typical spatial resolution of 5° by 5° grid over land and 10° by 10° grid over the Oceans, particularly in Southern Hemisphere

- The eddy covariance towers network with new towers has been expanded and inter-calibrated and they located in complex and highly disturbed landscapes; and across gradients of succession, stand age, and land-use intensity.
- Global soil carbon content is updated every 5 years on a 1° by 1° grid. Forest biomass changes is updated every 5 years or better and that the data from various national institutions are available on a geo-referenced basis
- On ocean surface basin-scale, an operational system of extensive in situ sampling of surface pCO_2 levels has been implemented.
- Land satellite products are evaluated and are ready to be used in process-based terrestrial ecosystems models.
- Ocean satellite products are evaluated and ready to be assimilated in operational oceanography models fitted with carbon cycle capabilities.
- Methods for evaluating land-ocean transfer have been tested and can now be applied
- New satellites are now in place for measuring column density of CO2 and other carbon compounds
- The modeling community is ready to ingest these data in the models to determine precisely the sources and sinks of carbon and the future evolution of carbon related compounds in the atmosphere.

Phase 4: Operations (2017 -   )

Section 9

Summary of *in situ* and space based data requirements

Remote-sensing Contribution to Providing Ecosystem Variables Relevant to Carbon Cycle Studies

Component of Surface-Atomosphere Carbon Flux	Global Observation Required	Existing, Approved, or Proposed Instruments / Missions: Historic	Current and Near-term	Through 2010	Future	Other Contributing Remote Sensors	Potential New Missions	Spatial Sampling Frequency	Temporal Sampling Frequency
Surface fluxes inverted from atmospheric CO2 measurements	Atmospheric CO_2 variability	HIRS-2	LWIR : AIRS, IASI SWIR : SCIAMACHY	OCO GOSAT	Active CO_2 sensors	IIP (FPI and LIDAR)		1-50 km	Daily *
Attribution of surface fluxes to combustion processes	Atmospheric CO variability		MOPITT SCIAMACHY	TES				25 km	Daily *
	Atmospheric BC aerosols variability	TOMS POLDER-I		CALIPSO POLDER-II APS		NPOES Cris		1-50 km	Daily *
Land-atmosphere CO_2 flux and terrestrial carbon processes	Land cover type Land cover change Burned areas	AVHRR LandSat1-7 SPOT1-5 AVNIR	AVHRR LandSat1-7 SPOT1-5 MODIS GLI ASTER MERIS AVNIR-2	SPOT1-5 LDCM NPOES VIIRS Prep. Prog.	NPOES VIIRS	AVIRIS AIRSAR	Synergistic multispectral optical + multifrequency polarimetric radar	30 m and 250-1.000 m	weekly
	Biophysical products:	AVHRR Landsat 1-7	AVHRR Landsat 1-7						

	LAI, FAPAR, Albedo…		MERIS MODIS SeaWIFS	LDCM ALOS ASTER		AIRSAR	Synergistic multispectral optical, radar missions Hyperspectral Mission e.g. SPECTRA	25-1000 m	w eekly
	Vegetation Productivity		SPOT-4-5 (Vegetation/HRG)						
				METOP-1-2-3…					
				MSG/SEVIRI					
				NPOES VIIRS Prep. Prog.	NPOES VIIRS	NPOES CrIs			
	Vegetation architecture or profile		MISR			AIRSAR LVIS SLICER	VCL Wide-swath LIDAR + interferometric radar	25 - 250 m	Annually
	Fires hotspots		TRMM MODIS GLI ASTER						Daily
			AATSR		NPOES				
			ATSR		VIIRS				
	Biomass and regrowth	AVHRR					VCL, Wide-swath LIDAR + low -frequency polarimetric radar	50 – 100 m	Annualy
		SPOT JERS-1 ERS-1, ERS-2							
			ASAR RADARSAT	ALOS		AIRSAR LVIS SLICER			
Climate variables driving land-atmosphere fluxes	Soil moisture regime (surface and deep)	SSM I	ASAR	SMOS	NPOES CMIS	AIRSAR, IIP (UHF / VHF radar)	Higher-resolution radiometers, lower-frequency radars	5-50 km	3-day for surface, 10-day for depth

	Precipitation		TRMM	GPM, Follow –on missions, geosynchronous	DPR TRMM		5 km	Daily
	Cloud cover	AVHRR	MODIS CERES	CloudSat NPOES Prep Prog. NPOES METOP-1-2-3 MSG		Follow –on missions, geosynchronous	1 km	Daily

* longer temporal averaging may be needed to get desired precision

Component of Surface – Atmosphere Carbon flux	Global Observation Required	Existing, Approved, or Proposed Instruments / Missions				Other Contributing Remote Sensors	Potential New Missions	Spatial Sampling Frequency	Temporal Sampling Frequency
		Historic	Present and Near – term	Through 2010	future				
Land–atmosphere CH_4 flux	Atmospheric CH_4 variability	IMG	MOPITT AIRS SCIAMACHY	TES				25 – 100 km	TBD
	Biomass burning CH4 emissions	See fire spots and burned areas							
	Wetland extent	AVHRR				AIRSAR	Low -frequency polarimetric radar	25 m or less, and – 1 km	weekly
		LandSat 1-7							
		SPOT1-5							
		SIR-C ERS-1 JERS-1	ERS-2 ASAR	ALOS, LDCM					
Air–Sea CO_2flux	ERS1-2								
	Wind speed	ERS – 1-2	QUICKSCAT ASAR MERIS AMSR-E WindSat SeaWinds AMSR	ESA's Atmospheric Dynamic Explorer			ALPHASCAT Wind Lidar	25 km	Daily
	Sea surface	AVHRR			SBERS			1 Km	Daily

	temperature		ATSR AATSR	VIIRS NPOES Prep. Prog.	VIIRS NPOES	NPOES CrIS			
				METOP 1-2-3					
Ocean biogeochemistry	Chlorophyll Ocean colour Ocean productivity	CZCS POLDER-I	SeaWIFS MODIS POLDER-II ADEOSII GLI	SGLI		SIMBIOS A / C particulate LIDAR		1 km	Daily
			MERIS	VIIRS NPOES PrepProg.	VIIRS NPOES				
Ocean circulation	Circulation & hydrography	TOPEX ERS-1	JASON–1 ENVISAT/ALTIMETER ERS-2	JASON–2				300 km	10 day

Space-based missions related to the Integrated Global Carbon Observations Theme

	Basin-scale Surface Observations *PCO2, carbonate system, Fluorescence, Nutrients, Optical properties, tracers, hydrography parameters*	Large scale inventories	Biogeochemical Time Series *pCO_2 sensors, sediment traps, trace metal samplers, and measurements of ocean optical properties*	Ocean Remote Sensing	Coastal Observations
Continuity challenges	- Ensure ongoing measurements from oceanographic research vessels, VOS, and SOOP vessels for surface pCO_2	- Continuity of shipboard surveys for each basin on a 5-10 year revisit time to track the penetration of anthropogenic CO_2, - Ensure co-ordinated sampling of hydrography parameters, nutrients, carbonate system, tracers, and biogeochemical species (iron, DOC and POC)	- Ensure continued support for existing time-series stations - Continuity of series of plankton species and abundance made through the Continuous Plankton Recorder Programme	- Ensure agency commitments for a transition from research missions to operational missions (operational data products and services…)	- Ensure continued support for developing a common network c coastal observing system elements
Knowledge Challenges	- Develop spatially and temporally extensive in situ sampling of surface pCO_2 - Develop co-sampling of other ecosystem and biogeochemical data to place pCO_2 data in proper context - Collect atmospheric data along the VOS lines (prec. 0.1 ppm) to better resolve regional budgets	- Develop autonomous carbonate system sensors that could be deployed on profiling floats	- Develop a network of quasi-autonomous ecological, bio-optical, and biogeochemical time series - Add new time-series stations in key remote locations (high latitude water formation regions of N. Atlantic, S. Ocean, ocean margins). - Development of automated techniques for measuring biogeochem. properties	- Develop satellite system to obtain higher ocean coverage (60% global, over a 3-5 day timeframe) - Develop systematic in-situ measurements to support satellite ocean colour (incorporated into VOS+time series)	- Establish a long-term observing network for coastal zones and ocean margins (use pilot studies for optimal design)

Priority observation for ocean component of global carbon observing system (source GOOS)

	Land cover and land use	Biomass	Seasonal Growth cycle	Fires / Disturbances	Solar radiation	Eddy-Covariance flux towers	Methane /Soil moisture and surface wetness	Canopy biochemistry
Continuity challenges	- Continuity of calibrated, fine resolution optical data from both fixed-view (eg Landsat) and pointable (eg SPOT) sensors - Continuity of calibrated, moderate resolution global satellite observations - Systematic reprocessing of satellite data to prepare time-stamped or time serie	- Ensure ongoing availability of canopy structure measurements - Improve availability and harmonization of inventories - More efficient use of national inventories (e.g. improved expansion factors…) - Ensure systematic obseration of forest by SAT (eg ALOS)	- Ensuring continuity of moderate resolution optical sensor measurements: same as for land cover - Ensuring agency commitments to generating global LAI products beyond the MODIS/TERRA period. - Ensuring continuity of moderate resolution optical sensor measurements	- Continuity of calibrated moderate resolution satellite data Burned areas (res <200 m needed). Fires hotspots (res ~ 1000 m) - Information on historical changes in fire regimes (long term satellite data + ground surveys)	- Ensuring the development and production of daily to monthly SW products.	- Continuity to maintain existing measurement programs for at least 10 years at a site - Expand the current network in underrepresented regions, and ecosystems undergoing disturbances Improving international coordination (on-line data transfer, data quality assurance)		
Knowledge challenges	- Obtain global land use information by means of satellite data at various spatial scales - Develop methods for deriving global land use information by means of satellite at various spatial scales, in linkge with the effect on carbon fluxes	- Expand inventories to Tropical forests, non-commercial forests, woodlands - Develop new soil carbon measurement techniques, and sampling strategies - Update the 1:5 million soil map of the world (underway) - Develop satellite technology for Remote sensing of biomass (eg SAR)	Use of new satellite techniques (lidar, multi-angle optical) to detect frost-free season duration at high latitudes Use of new satellite sensing techniques (multi-angle optical, lidar) to be further investigated for improving LAI accuracy at high LAI values and information on the distribution of sunlight within canopy	- Develop methods to quantify partial disturbances in forests (insect damage, selective harvesting) - Information on plume composition from satellite - Information on injection height - New methods to map areas burned by 'ground fires'	- Develop daily PAR products from geostationary and polar orbiting sensors. Spatial resolution near ~10 km and direct estimation for the PAR spectral region (0.4 - 0.7 um).	- Poof of "virtual tall towers" concept accurate CO_2 concentration measured at flux towers (< 1 ppm) - Standardize methodologies among the regional networks (joint ecological measurement, use of high resolution remote sensing, gap filling)	- Map the global distribution and temporal variability of wetland cover types - Develop satellite observation techniques and modeling tools to estimate methane fluxes from wetlands (include. Water table depth) - -Develop satellite-based capability to monitor global soil moisture	- Experimental programs to determine the operational feasibil of producing robust estimates of canop biochemical properties. (C and N content of pools)

Priority observation for terrestrial component of global carbon observing system (source TCO)

Land cover information					
Land Cover					
Water					
Snow and ice					
Barren or sparsely vegetated					
Built-up					
Croplands					
Forest	*Leaf type*	Needle	Broadleaf	Mixed	
	Leaf longevity	Evergreen	Deciduous	Mixed	
	Canopy cover	10 – 25 %	25 – 40 %	40 – 60 %	60 – 100 %
	Canopy height	0 – 1 m	1 – 2 m	> 2 m	
		(low shrub)	(tall shrub)	(trees)	
Forest special theme : flooded forest Spatial resolution : 1 km (coarse) and 25 m (fine) Update cycle 5 years (coarse and fine)					

Change information		
Change	Coarse	Fine
Resolution	1 km initially 250 m as soon as possible	25 m
Cycle	Annual wall – to – wall	5 year wall – to – wall 20% - 30 % annual
Classes	No change	No change
	Forest → non - forest	Forest → non - forest

	Non -forest ➔forest	Non - forest ➔ forest
Special products	Burned forest	Forest fragmentation Forest change occurrence

Satellite data requirements from for terrestrial observing system component

Fire information				
Fires	Spatial resolution	Revisit cycle	Data delivery	Source(s) of data
Fire monitoring Mapping burned area	250 – 1 km 25 m - 1 km	12 h Annual	12 h 3 months	Coarse resolution optical (thermal) Coarse and fine resolution optical with SAR backup
Modeling	250 m – 1 km	Annual	6 months	Coarse resolution optical plus land cover plus biomass, emission factors, etc.

Biophysical information					
Biophysical product	Units	Accuracy needed	Spatial resolution	Temporal cycle	Source of data
LAI	m^2/m^2	± 0.2 – 1.0	1 km	7 days	Coarse resolution optical
PAR	W/m^2	± 2 – 5 %	1 km	30 min – 1 day	Coarse resolution optical
FPAR	Dimensionless	± 5 – 10 %	1 km	7 days	Coarse resolution optical
Above ground biomass	G/m^2	± 10 – 25%	1 km	5 years	Inferred from land cover until spaceborne measurements are available
NPP	$Gc/m^2/yr$	± 20 – 30 %	1 km	1 year	Above products plus ground and spaceborne meteorological data

Satellite data requirements from for terrestrial observing system component (cont'd)

	Atmospheric Measurements	Atmospheric Transport modeling	Satellite CO2 observation
Continuity challenges	- Ensure commitment to stability of the flask sampling program. - Ensure frequent calibration of laboratories to the primary WMO standards - Continuity of intercomparison programmes for CO2, CH4 and other species - Adding key sites for flask sampling, over oceans based on network optimisation studies. - Develop in situ CO_2 analysis over continental areas - Continuity of vertical profile measurements begun as part of continental-scale carbon budget experiments.	- All data requirements to reduce uncertainties on spatial and temporal patterns of land-atmosphere and air-sea fluxes will help atmospheric studies to constrain regional carbon budgets	- Algorithm development to retrieve column integrated CO2 and CH4 abundances from existing sensors (AIRS, TOVS, SCIAMACHY)
Knowledge Challenges	- Develop multiple-species analysis, with new tracers (eg O2/N2, Ar/N2) - Develop sampling from tall towers, tethered balloons, and aircrafts in conjunction with ground measurements of fluxes and ecosystem condition (underway in Europe, North America, Siberia) - Expand atmospheric aircraft / tall towers measurements over tropical continents - Development work for deployment of robust remotely-operated continuous CO_2 and O2 analysers, with an acceptable trade-off between logistical independence and precision.	- Availability of location- and time-specific fossil fuel emission data (up to hourly, 10km) and bio-fuels - Availability and location of global fire emissions (timing, injection heights, emission factors, delayed emissions) - Archival and distribution of subgrid-scale vertical mass fluxes from operational weather analysis centres to facilitate transport modelling - Develop high resolution transport models in conjunction with land surface schemes	- Develop specific infrared CO_2 monitoring via satellite using the OCO mission and GOSAT (precision 1 ppm) - Model studies of the error structure for CO2 retrieval from space observations (role of diffusers, spectroscopy studies, diurnal cycle, inverse modeling of fluxes) - Develop assimilation framework in Numerical weather prediction models to assimilate radiances into CO2and fluxes - Development work for an active instrument to obtain CO2 vertical structure

Priority observation for atmospheric component of global carbon observing system

Ocean		Terrestrial		Atmosphere	
Diagnostic models	Generate carbon and biogeochemical fields that incorporate available data Interpolate and extrapolate pointwise observations Fusion of satellite observations Estimate bio-geochemical rates Optimal estimation of current sources and sinks Initial / Boundary conditions for prognostic models Design of optimal observation networks.	Diagnostic models e.g. Production Efficiency Models, Neural networks…	Generate continuous fields of NPP, e.g. directly from satellite measurements simulate short term variability of Net Ecosystem Exchange Prescribe fluxes to atmospheric transport models	**Global transport models** Global transport and climate models Numerical weather prediction models	I nverse and forward simulations of global CO2 (flask) network) Nverse and forward simulations of CO2. Can be coupled with ecosystem flux module interactively Can be used in addition for operational retrieval of CO2 atm from radiance and sources and sinks inferrence
Prognostic models Global ocean carbon models Coupled ocean-atm models with carbon	Required on a wide range of time and space scales, and with varying degrees of complexity of ecosystem biogeochemistry parameterization. Long integrations to examine the base state of the marine carbon cycle, natural interannual to geological variability Integrations for climate change responses and feedback	Prognostic models Carbon, Energy, water, prognostic models Energy, water, carbon, nutrients prognostic models Energy, water, carbon, nutrients prognostic models with disturbances and ecosystem dynamics	Long integrations to examine carbon pools and rates, and NEP Impact of nutrient addition and limitation Impact of land use and land management and disturbances on carbon pools and long term sequestration	**Regional transport and climate models** (100-10 km)	Inverse and forward simulations for interpreting continuous observations Generate climate fields to drive flux models Interpret synoptic variations and air masses CO2 variability
					Study atmospheric processes and carbon fluxes interactions

High-resolution mesoscale models basin-to-global models Coastal / Regional models		**Forestry models** **Agricultural models** …	Estimate biomass in managed forests in response to management action. Estimate yield of crop under different stress, and practice	**Local transport and climate models** (10 km-100 m) **Turbulent transport models**	near the ground (PBL) Campaign measurements interpretation Site effects modelling (eg mountain stations Canopy fluxesn recycling, etc…

Models for use in assimilating carbon cycle systematic observations

Notes

[1] Climate Change 2001: Synthesis Report: Third Assessment Report of the Intergovernmental Panel on Climate Change, in Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., and Johnson, C.A., eds.: Cambridge, United Kingdom and New York, NY, USA, Cambridge University Press, 881 pp.

[2] Climate Change 2001: Synthesis Report: Third Assessment Report of the Intergovernmental Panel on Climate Change, in Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., and Johnson, C.A., eds.: Cambridge, United Kingdom and New York, NY, USA, Cambridge University Press, 881 pp.

[3] **Need to add a more complete reference—web site?**

[4] **Add web site**

[5] **add web site**

[6] **add web site**

[7] ** add web site**

[8] See http://ioc.unesco.org/igospartners/igoshome.htm

[9] See http://www.ceos.org/

[10] See: http://ioc.unesco.org/iocweb/co2panel

[11] See **

[12] See **

[13] **Add a set of cites to National Program web sites**

[14] e.g., CMDL Flask Network (GLOBALVIEW-CO2 2000, Cooperative Atmospheric Data Integration Project- Carbon Dioxide: Boulder, Colorado, NOAA-CMDL)

[15] http://www-cger.nies.go.jp/~moni/flux/asia_flux/index.html, http://www.isa.utl.pt/def/gemf/carboeuroflux.htm, http://public.ornl.gov/ameriflux/Participants/Sites/Map/index.cfm, http://www.fluxnet-canada.ca/welcome.html, http://www.clw.csiro.au/research/waterway/interactions/ozflux/, http://www-eosdis.ornl.gov/FLUXNET/

[16] ** add cites to web sites **

[17] **add cite to FAO and IGBP Soil Maps

[18] http://ioc.unesco.org/ioccp

[19] **(web site loicz)

[20] ** Chédin**

[21] Which is flying on board the NASA/Aqua satellite that was launched in May 2002.

[22] The Inrared Atmospheric Sounder Interferometer (IASI) will fly with AMSU on board the EUMETSAT/MetOp that is scheduled for launch in 2005.

[23] Which will fly which will fly on the NOAA-NASA's NPOESS Prepatory Program (NPP) Mission as well on the NPOESS meteorological satellite.

[24] For instance, AIRS measures 2378 frequencies at high spectral resolution and covers most of the infrared spectrum while HIRS-2 measures 19 infrared frequencies.

[25] In particular, the 25-year archive of the HIRS-2 should be used to produce a CO_2 record at a space-time scale of 10^o/monthly and with a target precision of 1%.

[26] May, R.D. and Webster, C.R. 1990. "Balloon-borne Laser Spectrometer Measurements of NO2 with Gas Absorption Sensitivities Below 10-5", Appl. Opt. 29, 5042-5044. C.R. Webster, C.R. and May, R.D. 1991. Aircraft Laser Infrared Absorption Spectrometer (ALIAS) for Polar Ozone Studies", Infrared Technology XVII, 1540, 187-194. Webster, C.R. and May, R.D. 1992. "In-Situ Stratospheric Measurements of CH4, 13CH4, N2O, and OC18O Using the BLISS Tunable Diode Laser Spectrometer", Geophys. Res. Letters 19, 45-48. Michelson, H.A. et al. 1999. "Intercomparison of ATMOS, SAGE II, and ER-2 observations in the Arctic vortex and extra-vortex air masses during spring 1993", Geophys. Res. Letters, 26, 291-294. Zahniser, M. S. et al. 1995. "Measurement of trace gas fluxes using tunable diode laser spectroscopy." Phil. Trans. R. Soc. Lond. A, 351, 371-382. Nelson, D.D. et al. 1996. "Recent Improvements in Atmospheric Trace Gas Monitoring Using Mid-infrared Tunable Diode Lasers." SPIE Proceedings, Vol. 2834, 148-159.

[27] http://www.wmo.ch/wmo50

[28] http://www.ioc.unesco.org/goos

[29] http://ioc.unesco.org/iocweb

[30] http://www.fao.org/gtos

[31] http://www.fao.org

[32] http://www.unep.org